The Shape of CMB Focal Planes to Come

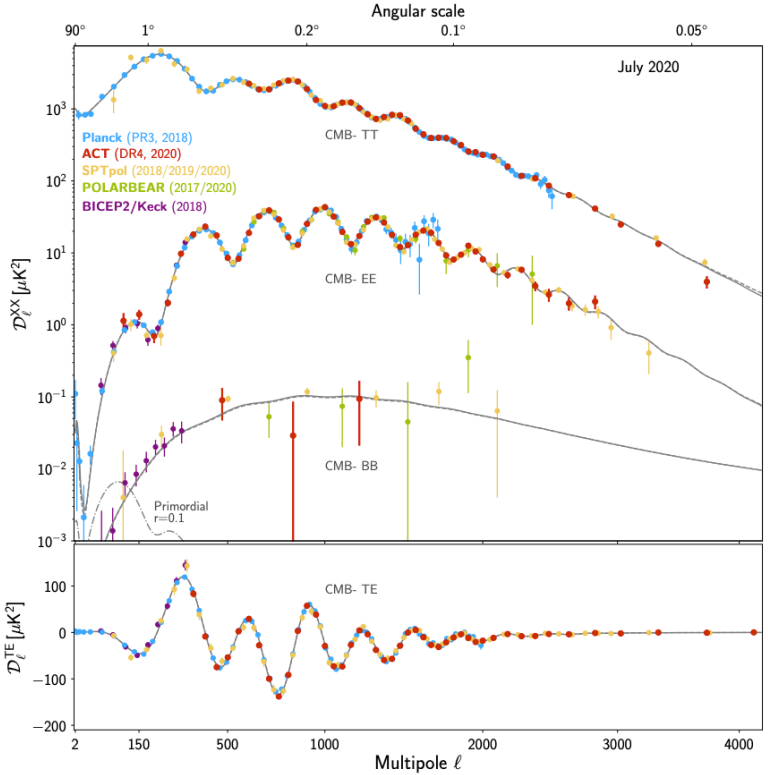
Johannes Hubmayr

Quantum Sensors Group, National Institute of Standards and Technology

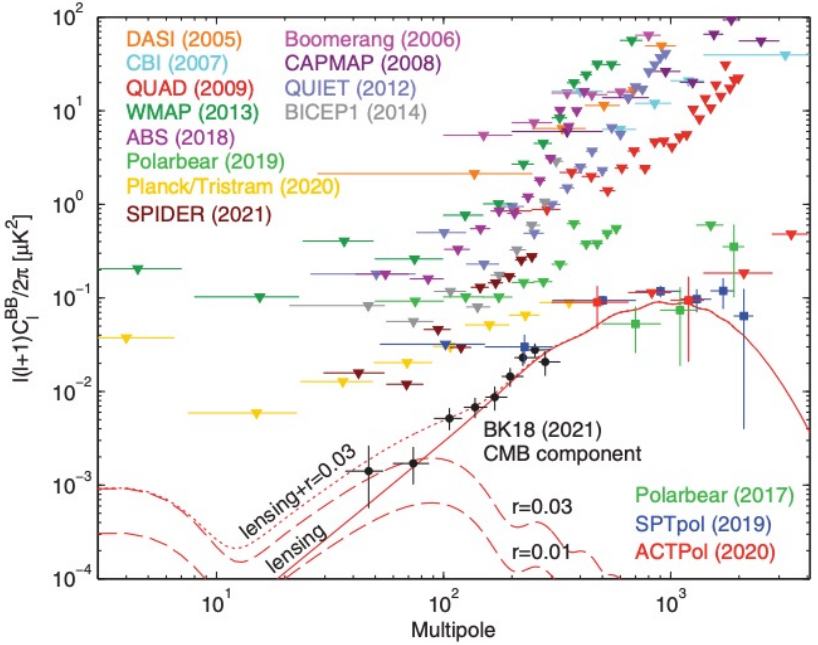
From Planck to the Future of CMB

Monday May 23, 2022

Precision Cosmology Enabled by Sensor Array Developments



Steve K. Choi *et al* JCAP12(2020)045



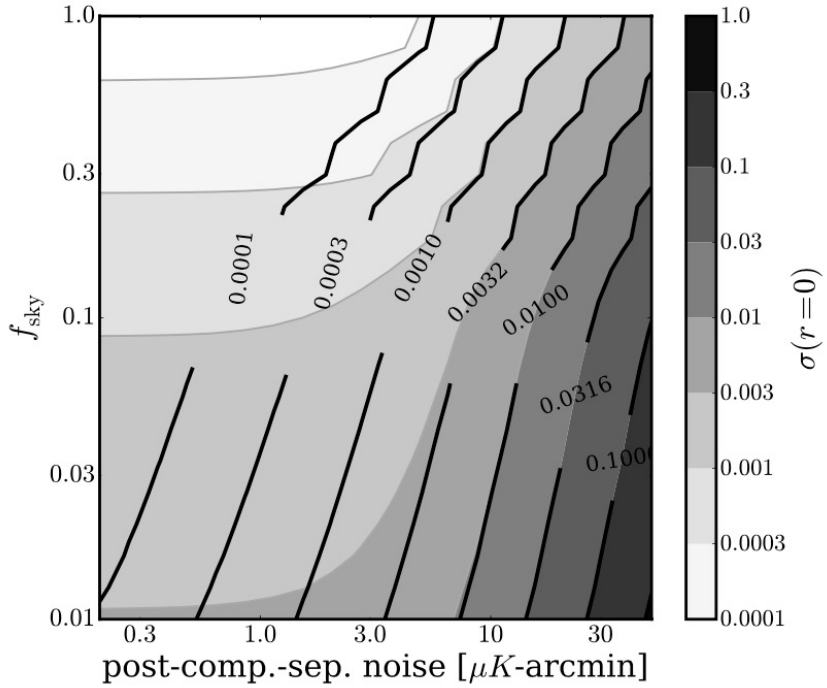
PHYSICAL REVIEW LETTERS **127,** 151301 (2021)

Single detector observation time to reach current r limits

$$T_{obs} = \left(\frac{NET_{cmb}}{map\ depth}\right)^2 \frac{f_{sky}}{\eta}$$

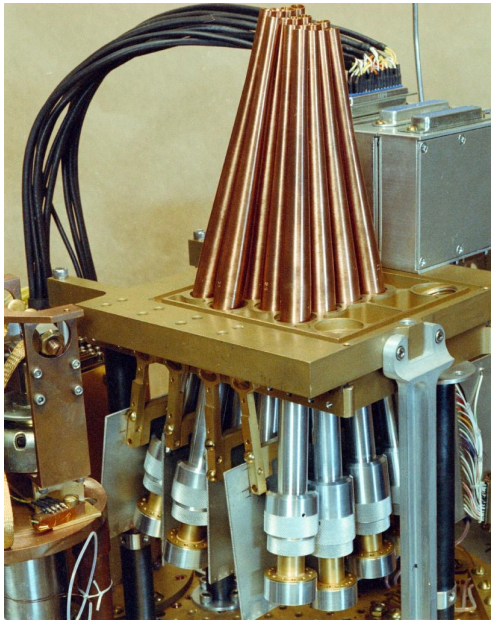
r < 0.036 @ 2σ (BK18) -> fsky = 0.1, map depth = 20 uK-arcmin, η=1

Detector	NET_{cmb}	T_{obs} (yrs)
Noiseless detector	27 uK√s	0.9
Space	40 uK√s	1.9
Ground	200 uK√s	47

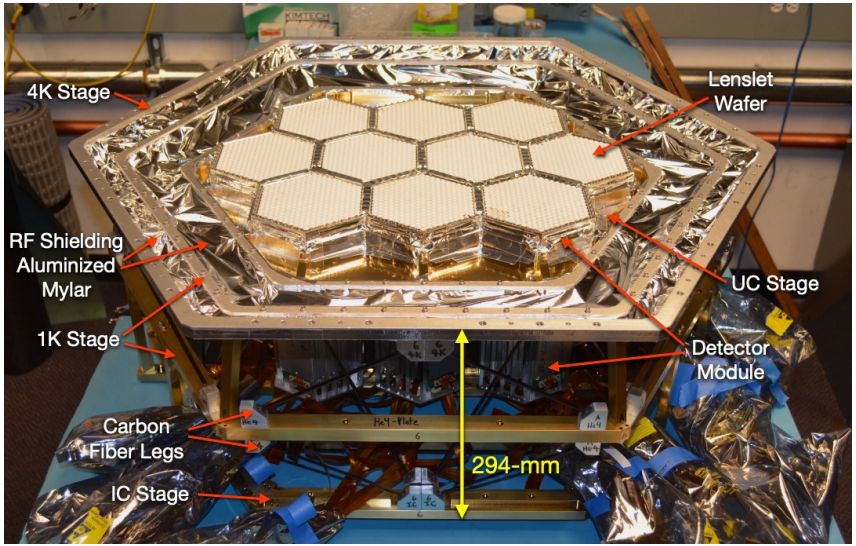


J. Errard et al. JCAP03(2016)052

Focal Planes Past and Present



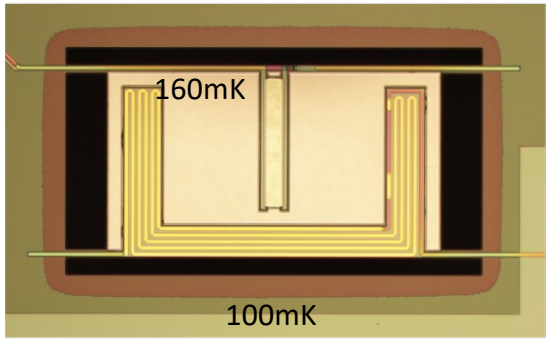
B. Rabii et al Rev Sci Inst **77**, 071101 (2006)

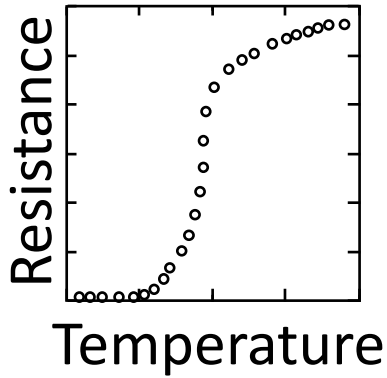


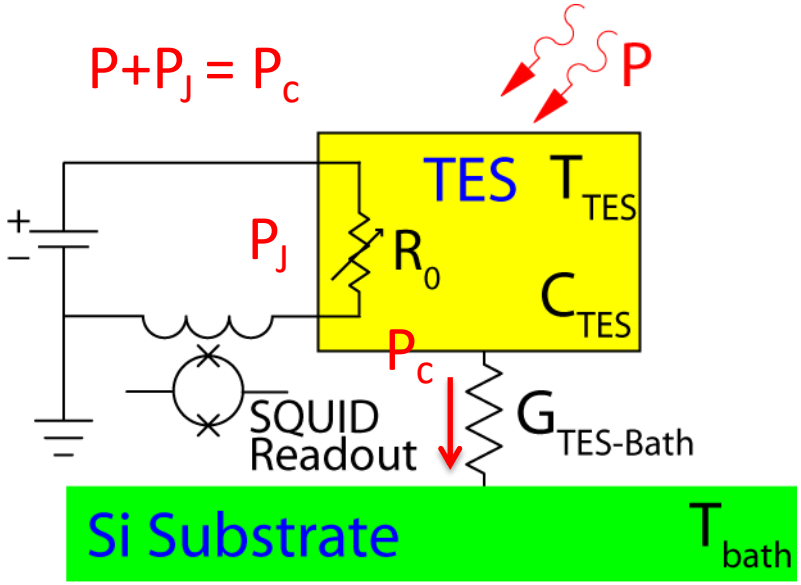
J. A. Sobrin *et al* 2022 *ApJS* **258** 42

Trend: more sensors, more on-chip capability

Transition Edge Sensor (TES) bolometer



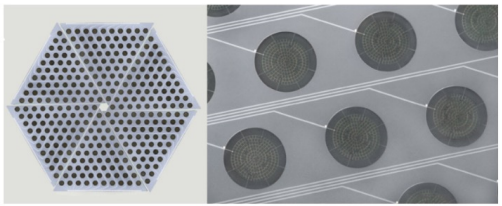




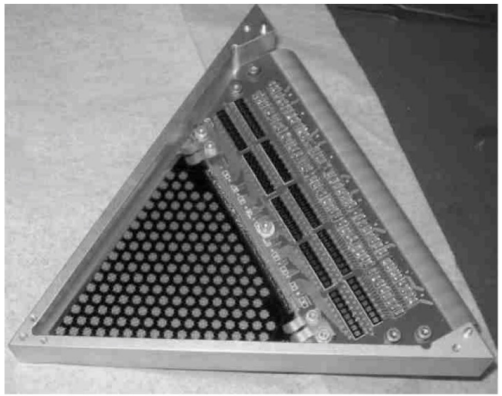
Credit: Doug Bennett

- Relative power meter that works by principle of electrical substitution
- Noise of device less than photon noise ($NEP^2 = 2h\nu P$ for narrow band signal)
- TES may be fabricated in arrays
- Multiplexed Superconducting QUantum Interference Device (SQUID) readout

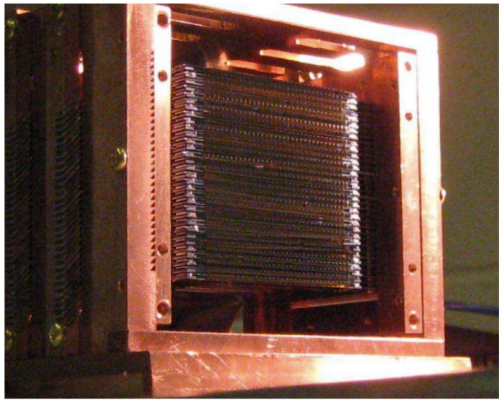
Early CMB bolometer array examples



APEX-SZ (UC, Berkeley)

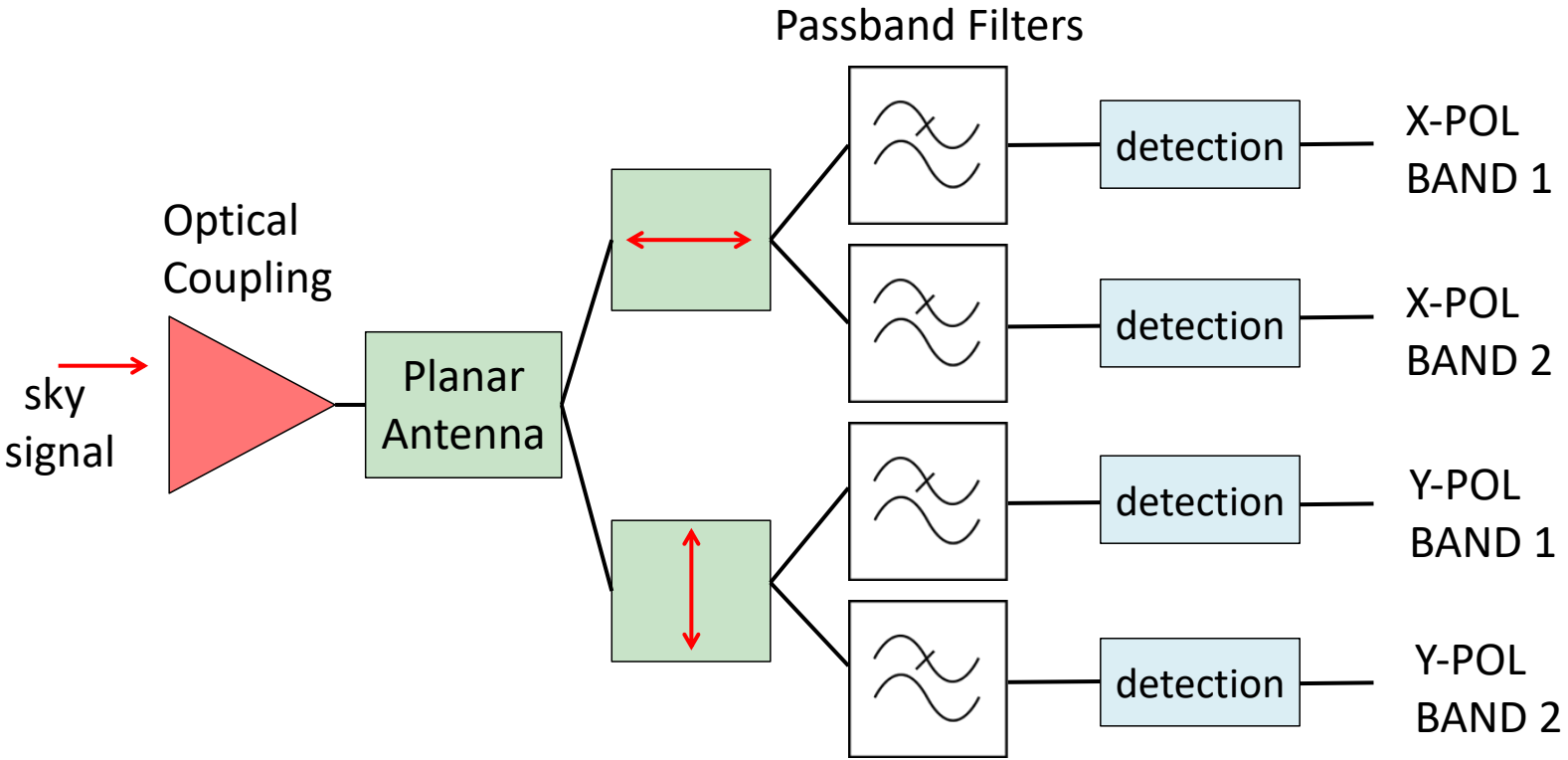


SPT wedge (UC, Berkeley)



ACT pop-up detectors (NASA, Goddard)

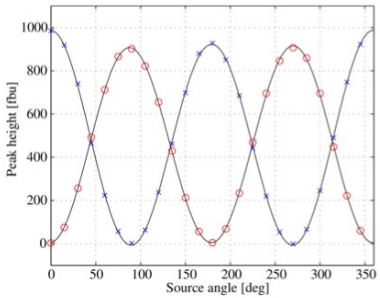
Detection schematic

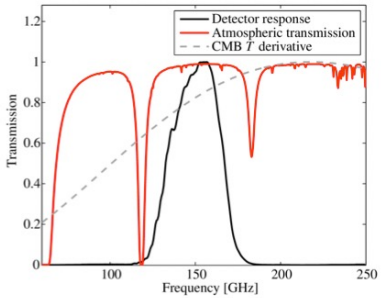


Antenna-coupled TES arrays

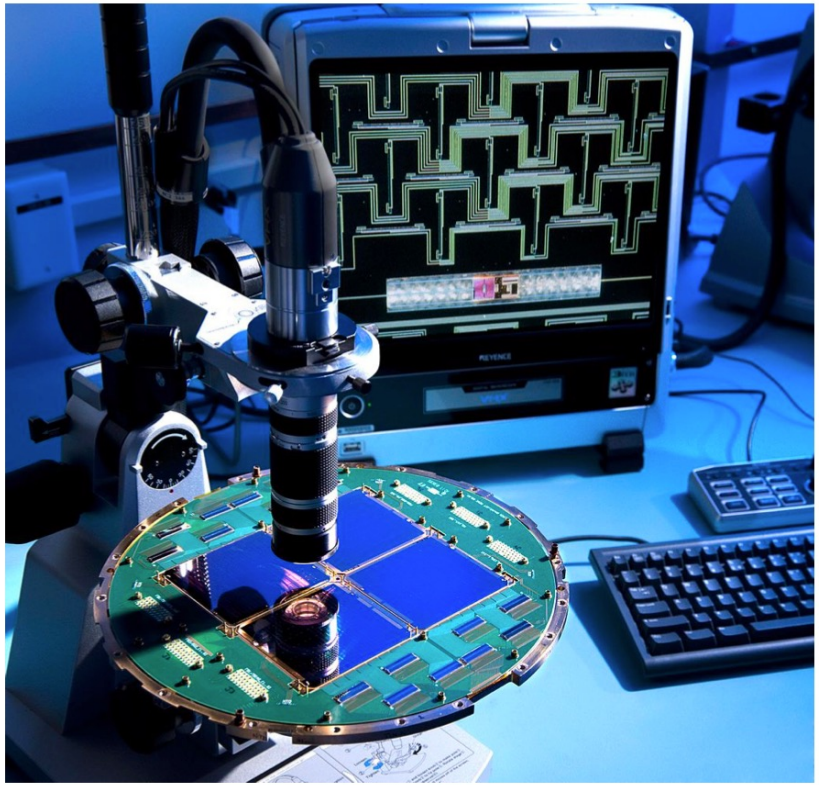
More on-wafer capability

1. Integrated optical coupling
2. Polarization sensitivity
3. on-chip passband definition



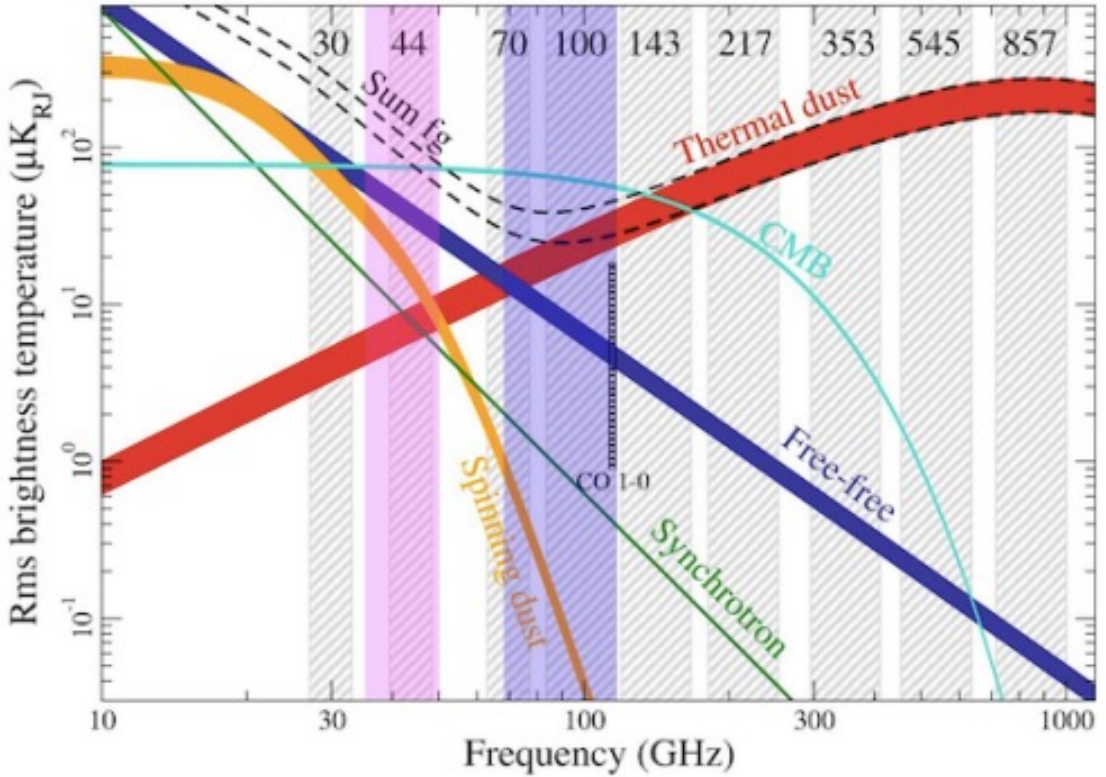


ApJ **792**, 62, 2014

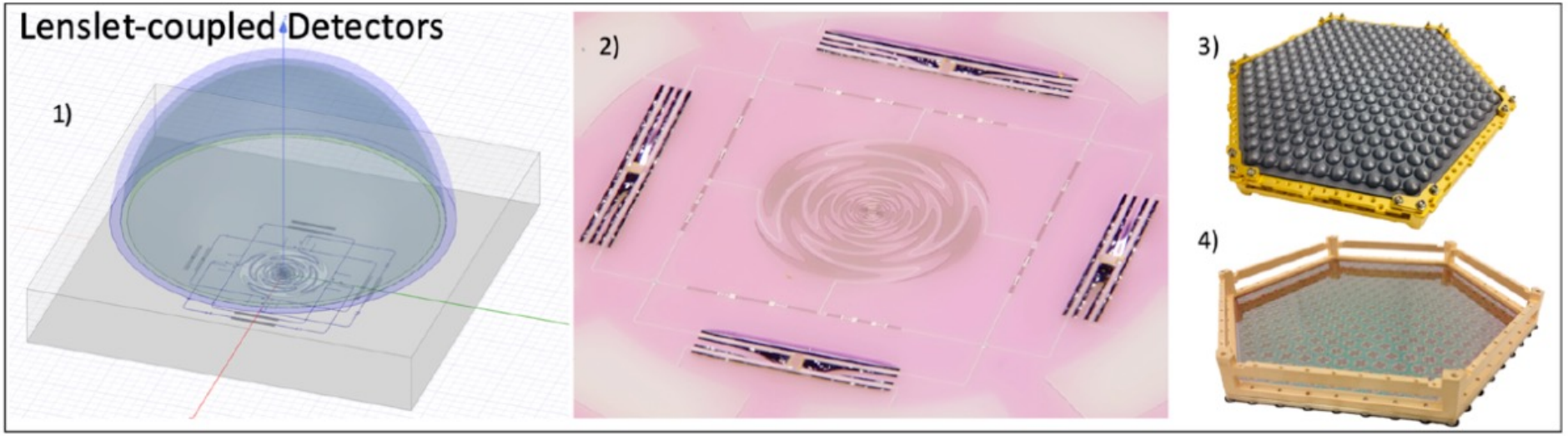


BICEP2 focal plane (Caltech/JPL)

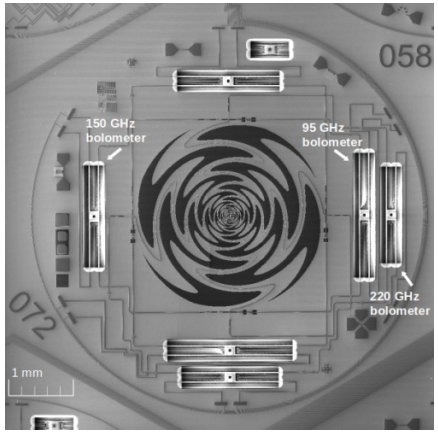
Frequency Coverage -> Multichroic Detectors

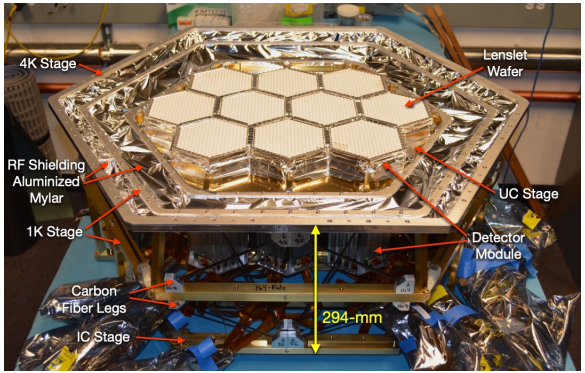


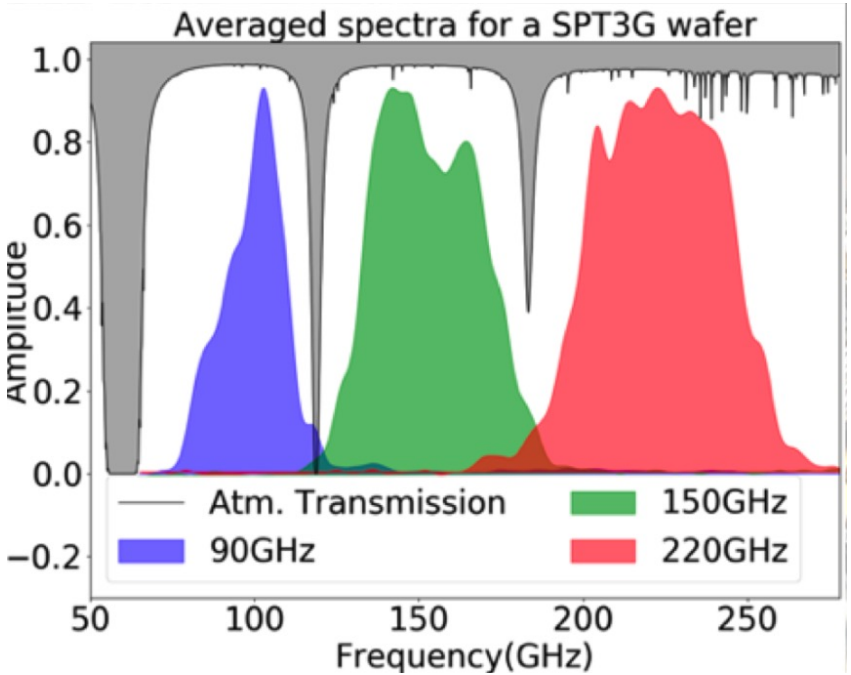
Lenslet-coupled TES arrays



Sinuous antenna 3:1 bandwidth



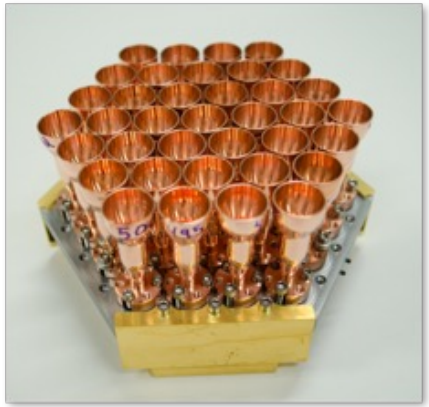


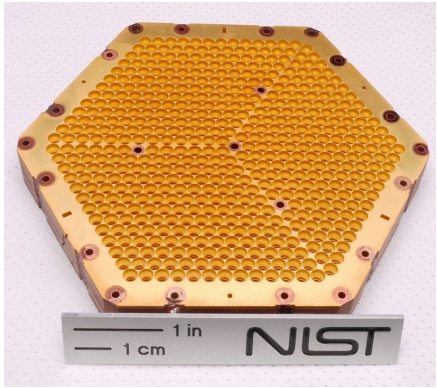


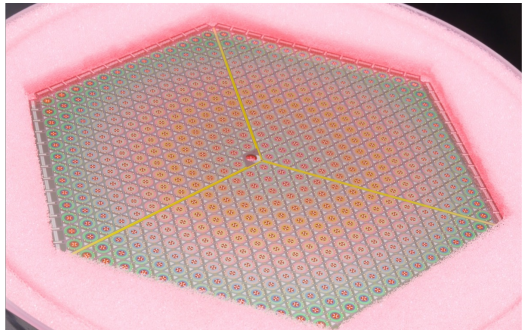
Anderson et al 2018

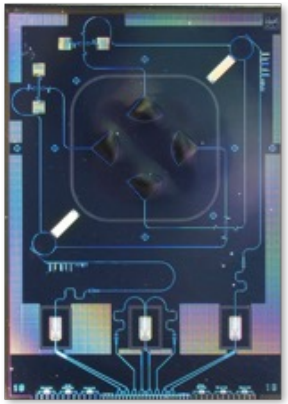
Feedhorn/OMT-coupled

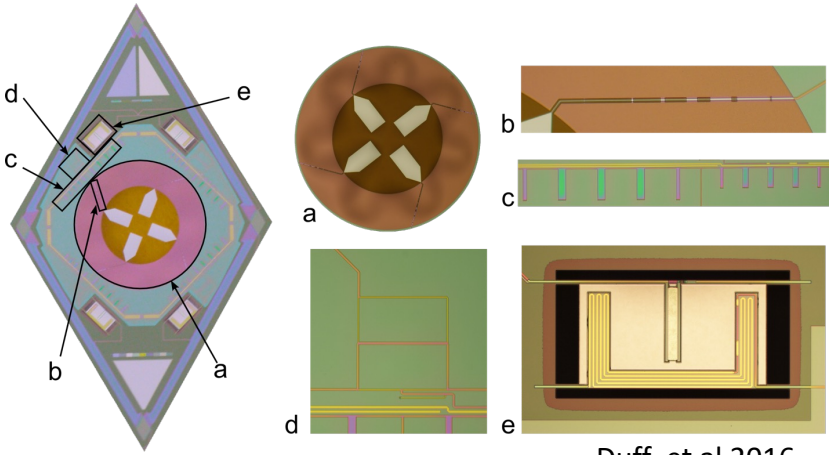
NASA/Goddard





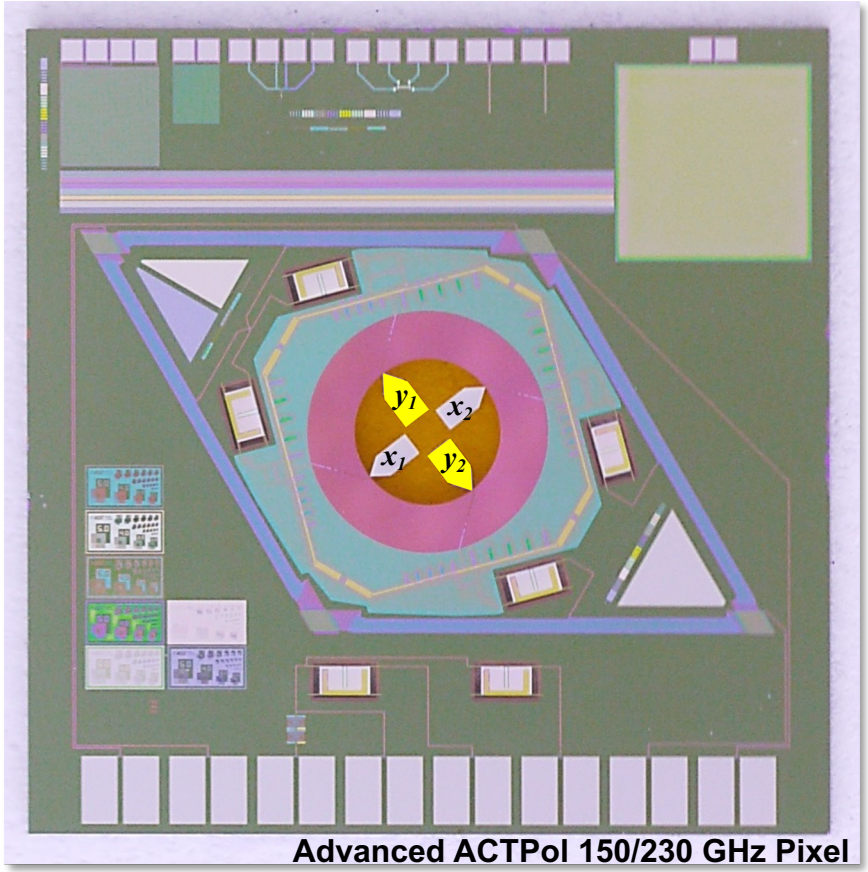




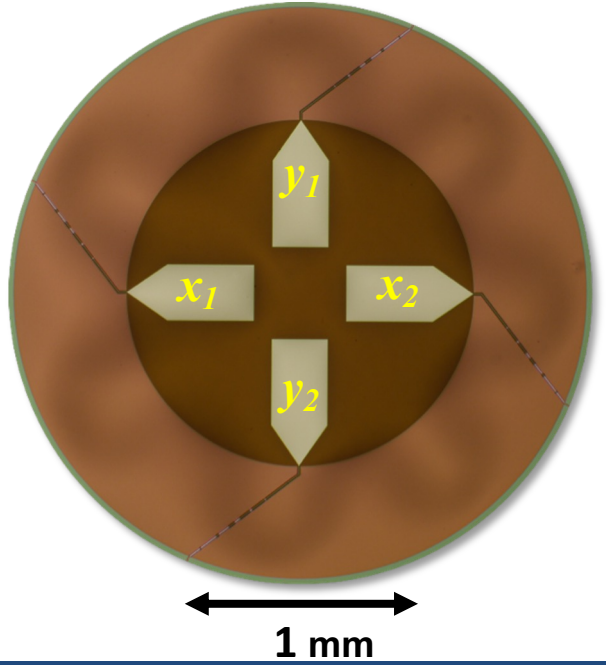


Duff et al 2016

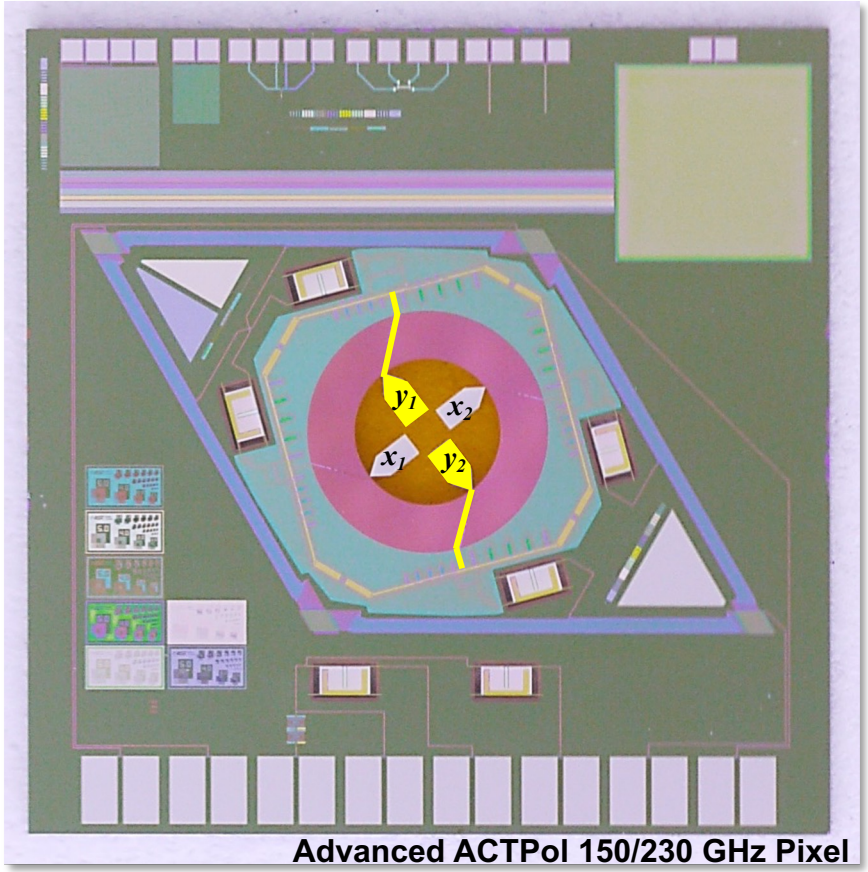
CMB polarimeter



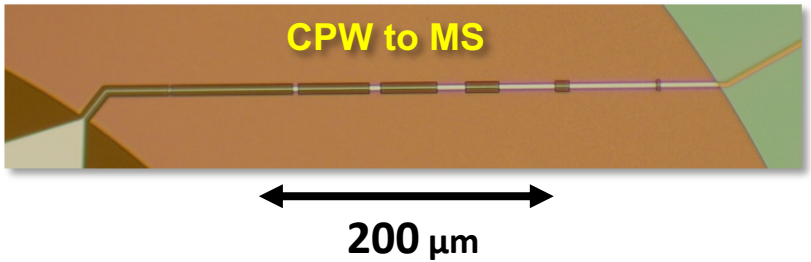
- Planar orthomode transducer (OMT) separates x & y linear polarizations



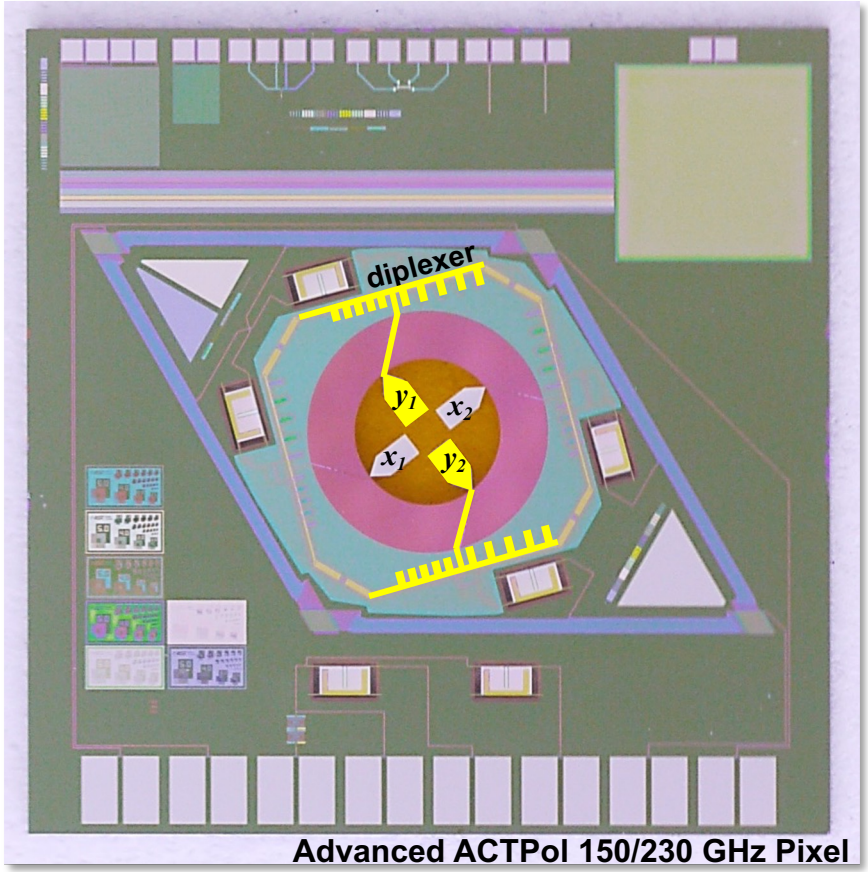
CMB polarimeter



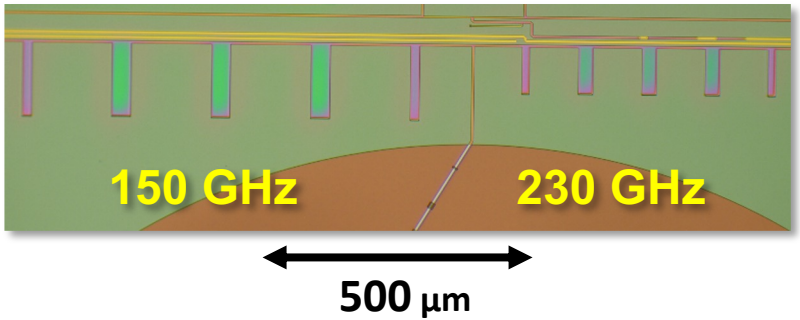
- Planar orthomode transducer (OMT) separates x & y linear polarizations
- CPW to MS transition



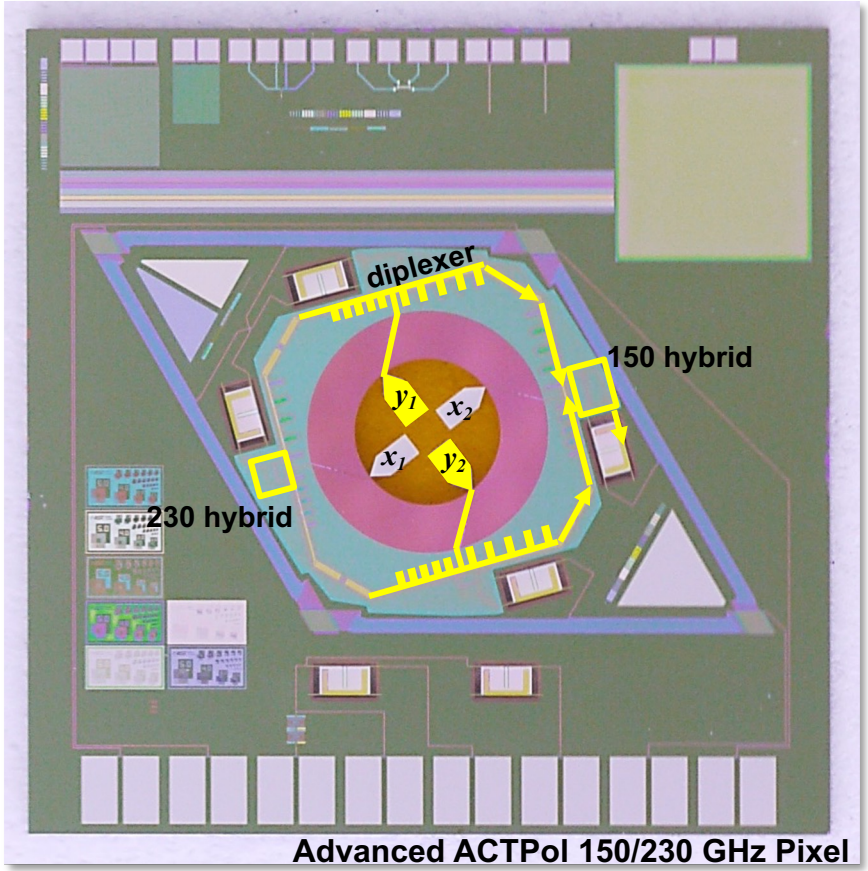
CMB polarimeter



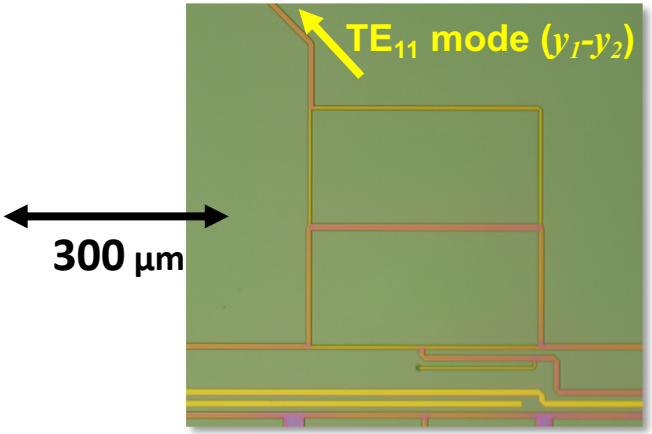
- Planar orthomode transducer (OMT) separates x & y linear polarizations
- CPW to MS transition
- Filter into two bands



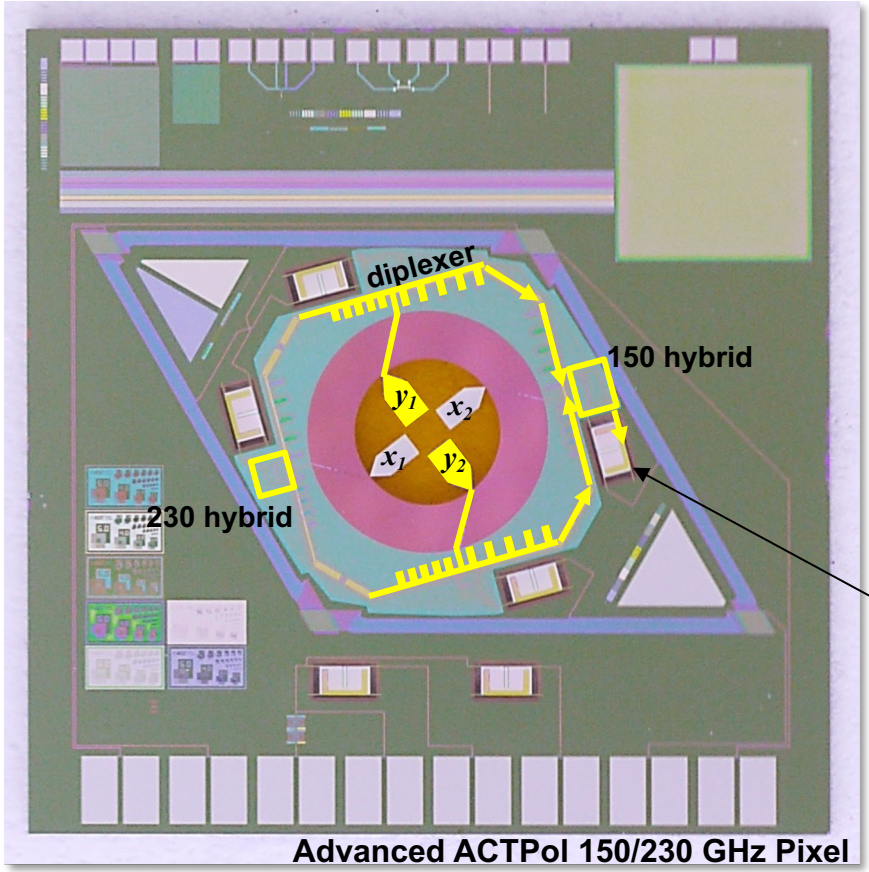
CMB polarimeter



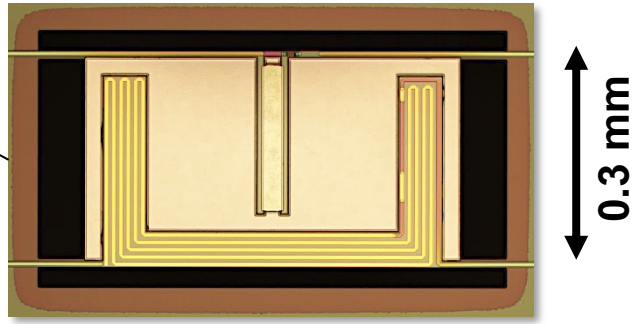
- Planar orthomode transducer (OMT) separates x & y linear polarizations
- CPW to MS transition
- Filter into two bands
- Combine lowest order mode/ reject others



CMB polarimeter



- Planar orthomode transducer (OMT) separates x & y linear polarizations
- CPW to MS transition
- Filter into two bands
- Combine lowest order mode/ reject others
- Power sensed with TES bolometer



Detector technology for active/planned experiments

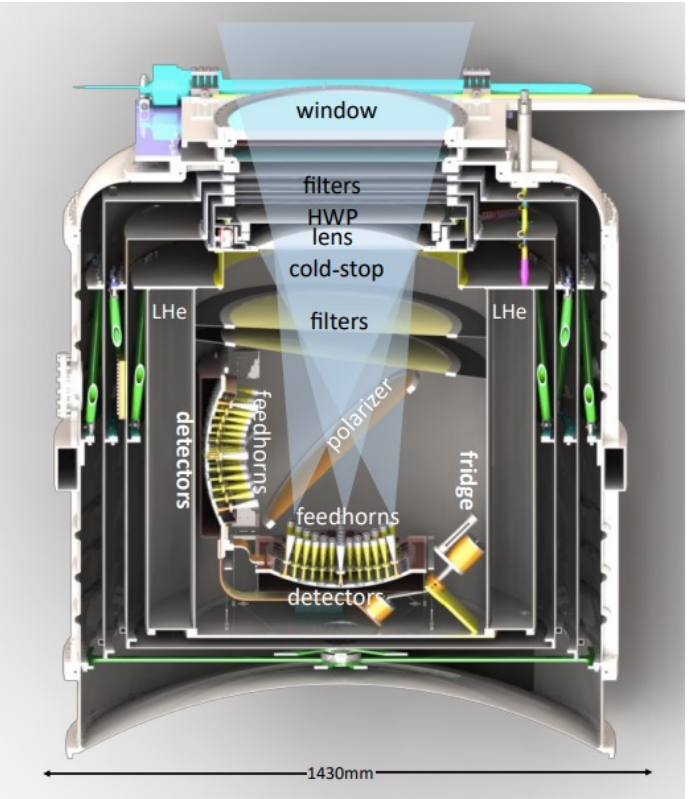
Detector type	Deployed	Planned/in-development
Antenna	BICEP2, SPIDER,KECK, BICEP3, BICEP Array	BICEP Array
Lenslet	Polarbear, PB2/Simons Array, SPT-3G, GroundBIRD	Simons Observatory, LiteBIRD, GroundBIRD
Feedhorn/planar OMT	ABS, SPTpol, ACTPol, Advanced ACTPol, CLASS, GroundBIRD	AliCPT, Simons Observatory, LiteBIRD, Taurus, CMBS4
direct absorber	PIPER, LSPE/SWIPE*	QUBIC**
coherent	QUIJOTE, LSPE/STRIP	

*with multi-moded feed-coupling
** with switching horn array

Need more light, not necessarily more detectors

- 326 spider-web TES bolometers
- 8800 EM modes
- More modes -> decreased angular resolution

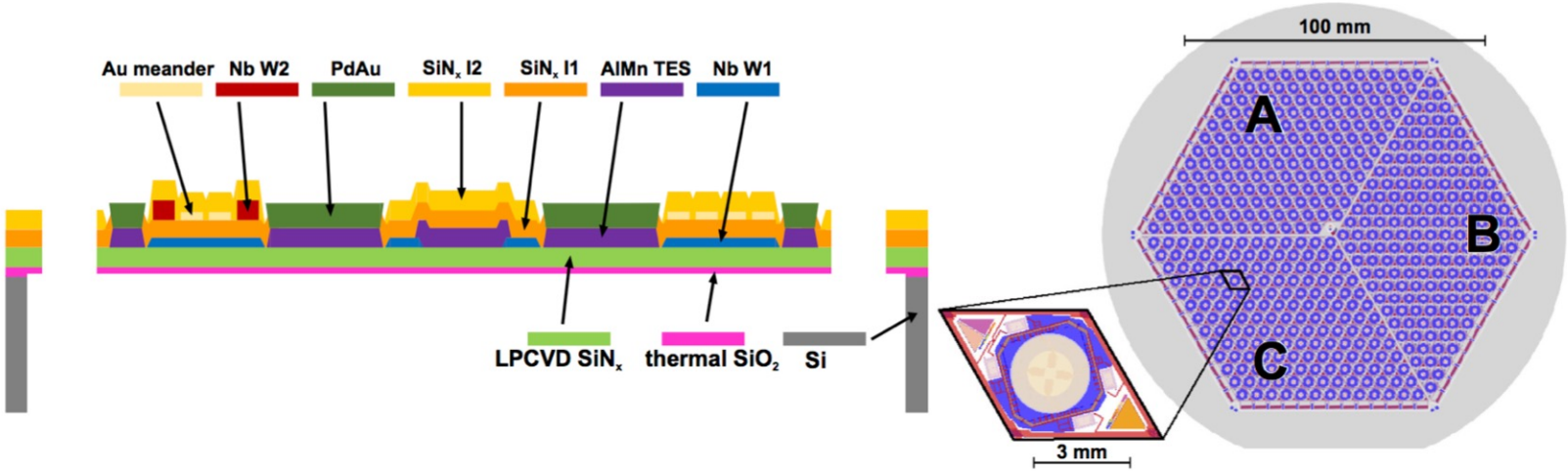
LSPE-SWIPE



Addamo et al. JCAP 2021

Advances enabled by microfab

OMT-coupled fabrication process

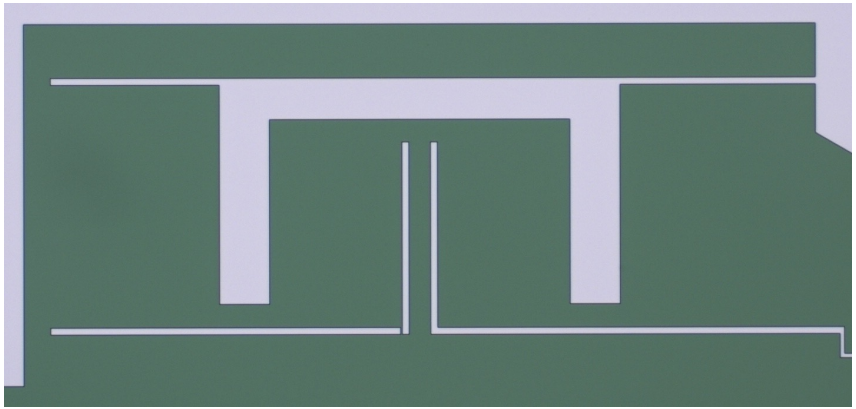


Duff et al. JLTP 184 (2016)

- 7 lithography levels
- Four metals, three dielectrics
- 10+ fabrication steps

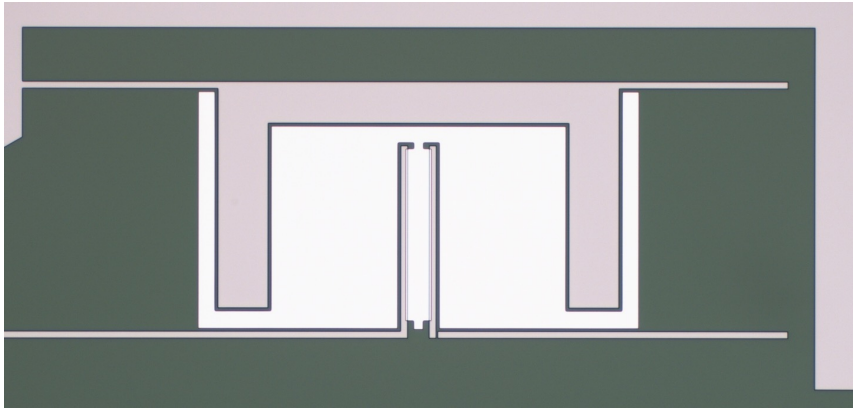
TES bolometer fabrication process

1. SiOx +SiN
2. 1st Nb layer
3. TES
4. 1st insulator layer
5. 2nd Nb layer
6. Au term resistor
7. 2nd insulator layer
8. PdAu
9. FSP (thermal isolation definition)
10. Deep Etch



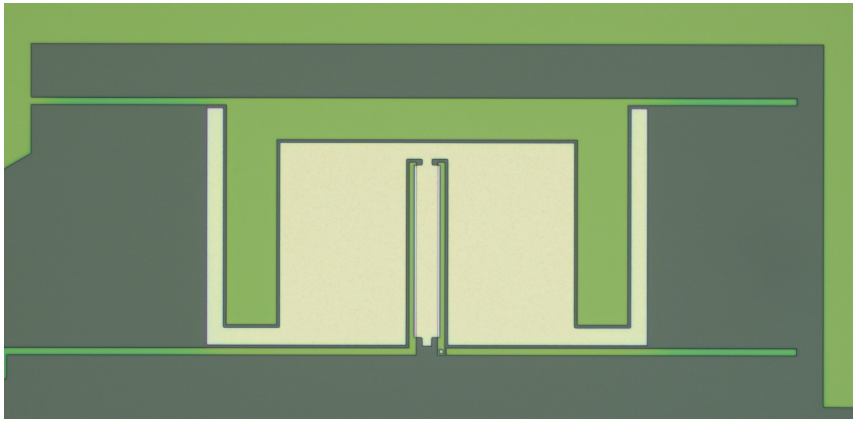
TES bolometer fabrication process

1. SiOx +SiN
2. 1st Nb layer
3. TES
4. 1st insulator layer
5. 2nd Nb layer
6. Au term resistor
7. 2nd insulator layer
8. PdAu
9. FSP (thermal isolation definition)
10. Deep Etch



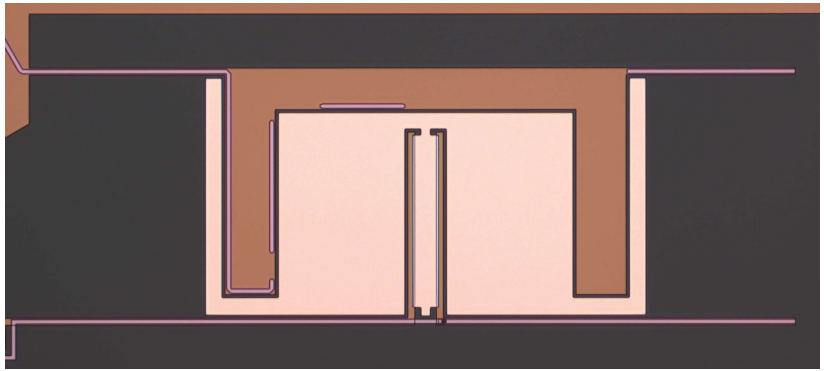
TES bolometer fabrication process

1. SiOx +SiN
2. 1st Nb layer
3. TES
4. 1st insulator layer
5. 2nd Nb layer
6. Au term resistor
7. 2nd insulator layer
8. PdAu
9. FSP (thermal isolation definition)
10. Deep Etch



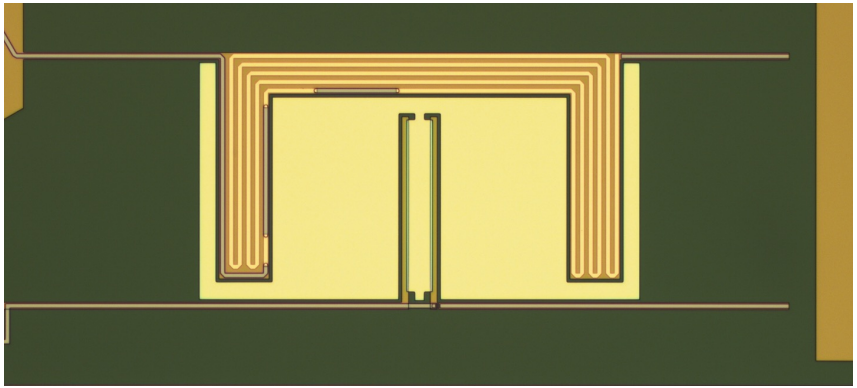
TES bolometer fabrication process

1. SiOx +SiN
2. 1st Nb layer
3. TES
4. 1st insulator layer
5. 2nd Nb layer
6. Au term resistor
7. 2nd insulator layer
8. PdAu
9. FSP (thermal isolation definition)
10. Deep Etch



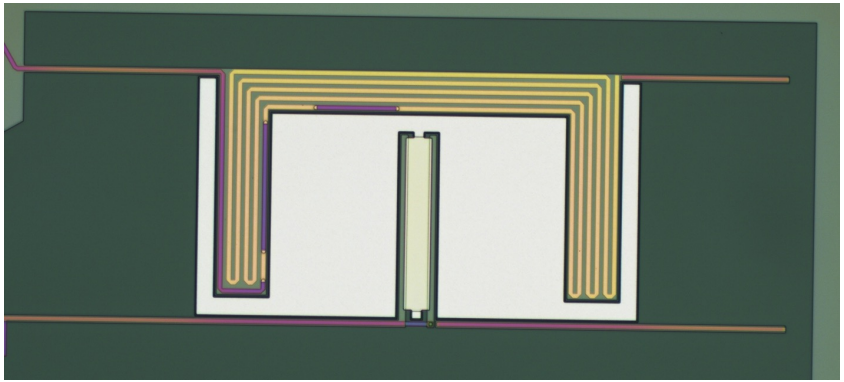
TES bolometer fabrication process

1. SiOx +SiN
2. 1st Nb layer
3. TES
4. 1st insulator layer
5. 2nd Nb layer
6. Au term resistor
7. 2nd insulator layer
8. PdAu
9. FSP (thermal isolation definition)
10. Deep Etch



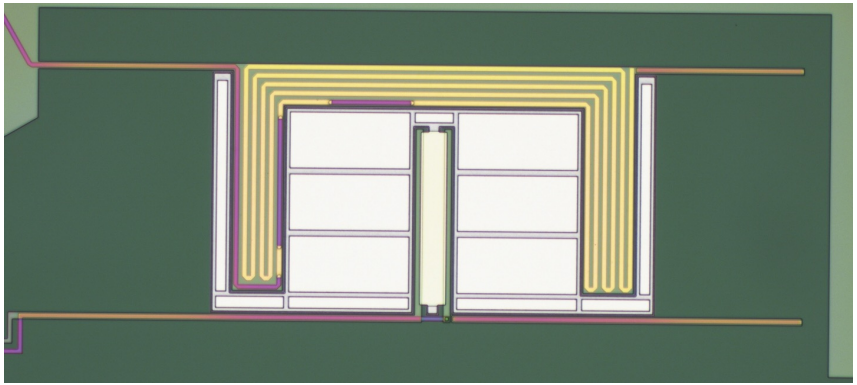
TES bolometer fabrication process

1. SiOx +SiN
2. 1st Nb layer
3. TES
4. 1st insulator layer
5. 2nd Nb layer
6. Au term resistor
7. 2nd insulator layer
8. PdAu
9. FSP (thermal isolation definition)
10. Deep Etch



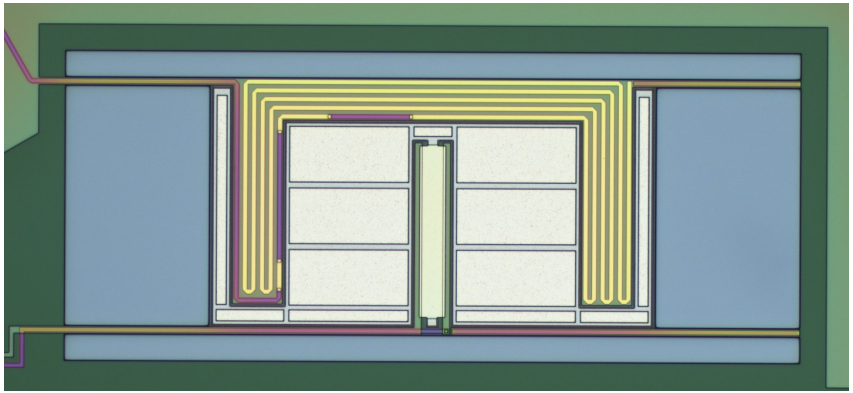
TES bolometer fabrication process

1. SiOx +SiN
2. 1st Nb layer
3. TES
4. 1st insulator layer
5. 2nd Nb layer
6. Au term resistor
7. 2nd insulator layer
8. PdAu
9. FSP (thermal isolation definition)
10. Deep Etch



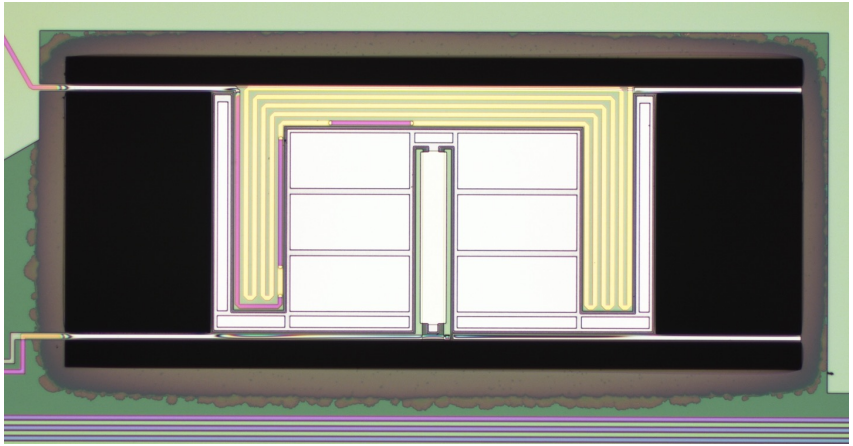
TES bolometer fabrication process

1. SiOx +SiN
2. 1st Nb layer
3. TES
4. 1st insulator layer
5. 2nd Nb layer
6. Au term resistor
7. 2nd insulator layer
8. PdAu
9. FSP (thermal isolation definition)
10. Deep Etch

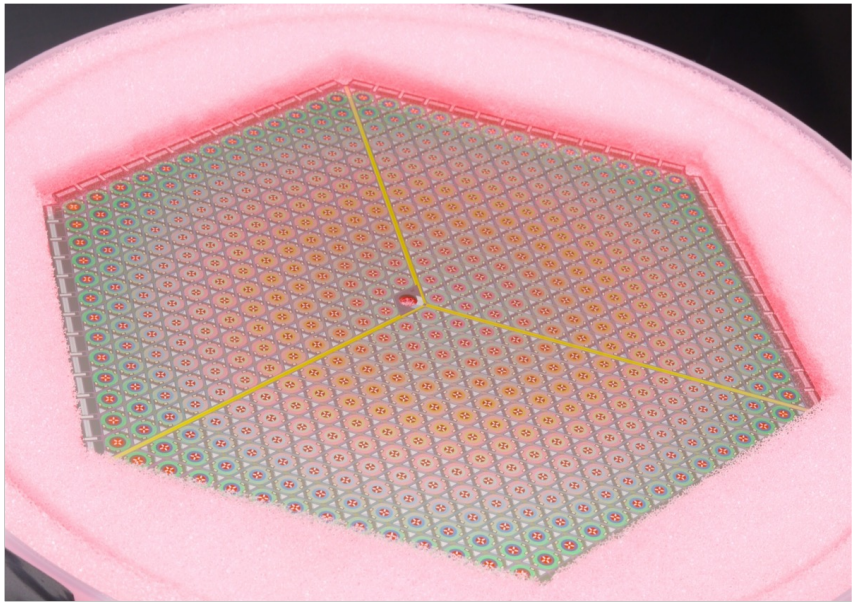


TES bolometer fabrication process

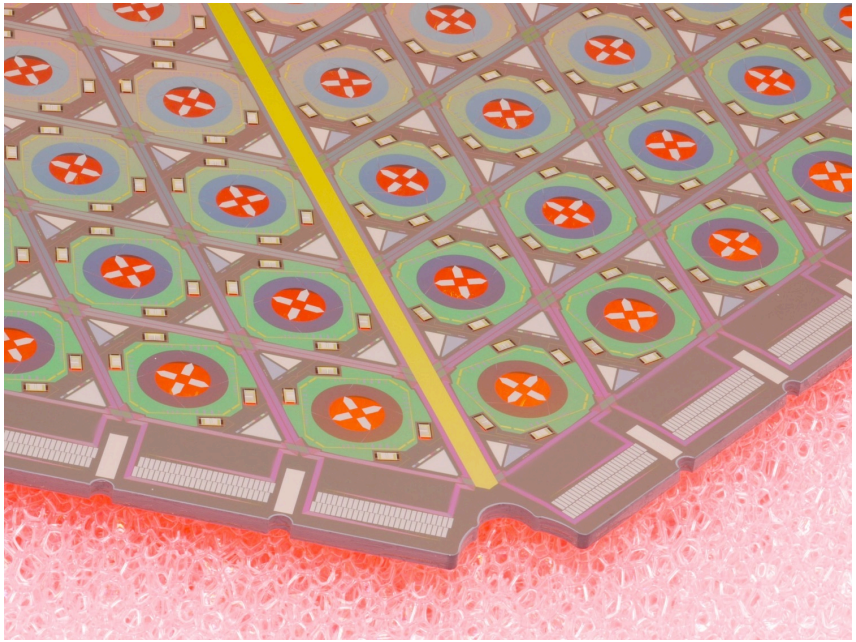
1. SiOx +SiN
2. 1st Nb layer
3. TES
4. 1st insulator layer
5. 2nd Nb layer
6. Au term resistor
7. 2nd insulator layer
8. PdAu
9. FSP (thermal isolation definition)
10. Deep Etch



Completed Array



506 spatial pixel

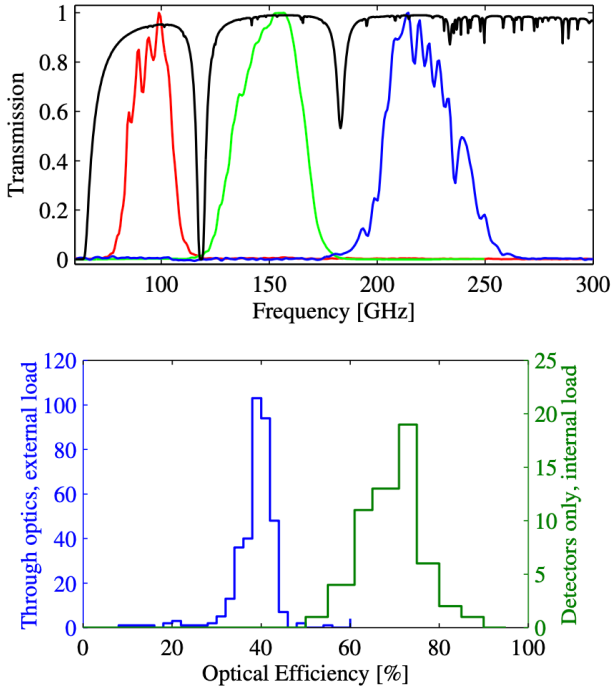


unit cell size = 4.75mm

Superconducting IC array performance

Antenna-coupled TES Bolometers used in BICEP2, Keck Array, and SPIDER

The BICEP2, Keck Array, and SPIDER Collaborations, ApJ 812, 176, 2015



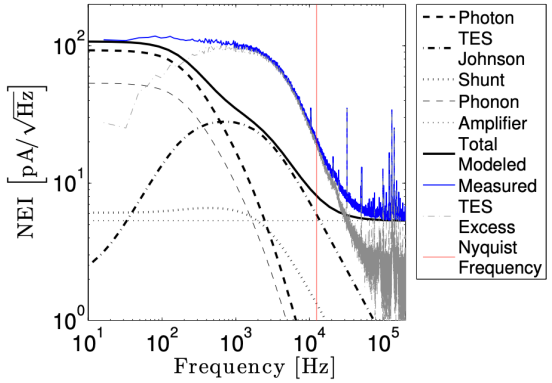


FIG. 20.— Measured and modeled noise for a single detector in the *Keck Array*. The red line indicates the Nyquist frequency for the multiplexing rate.

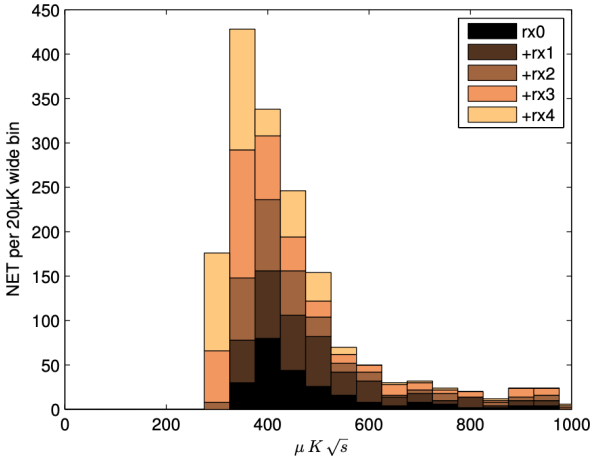
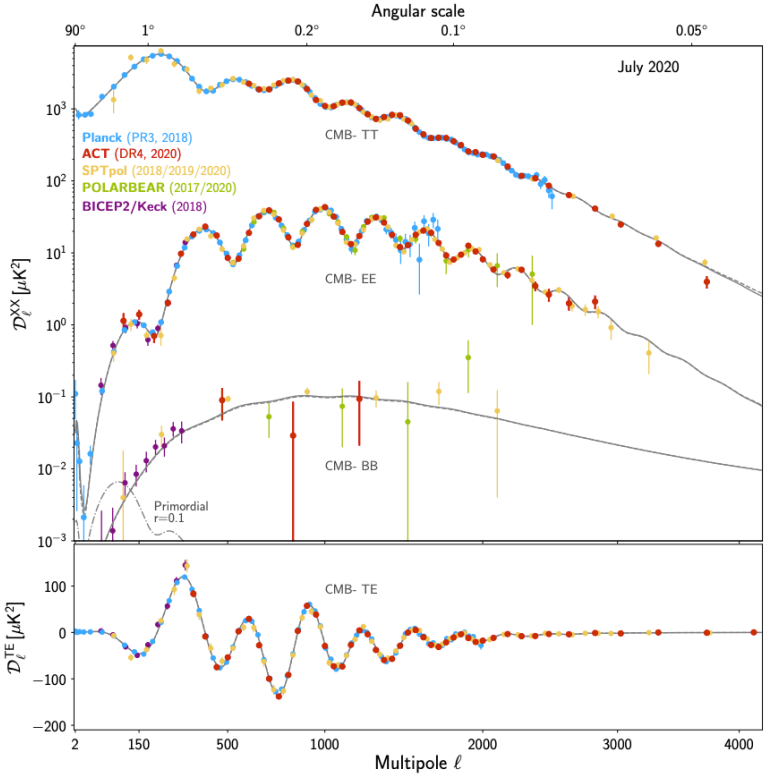
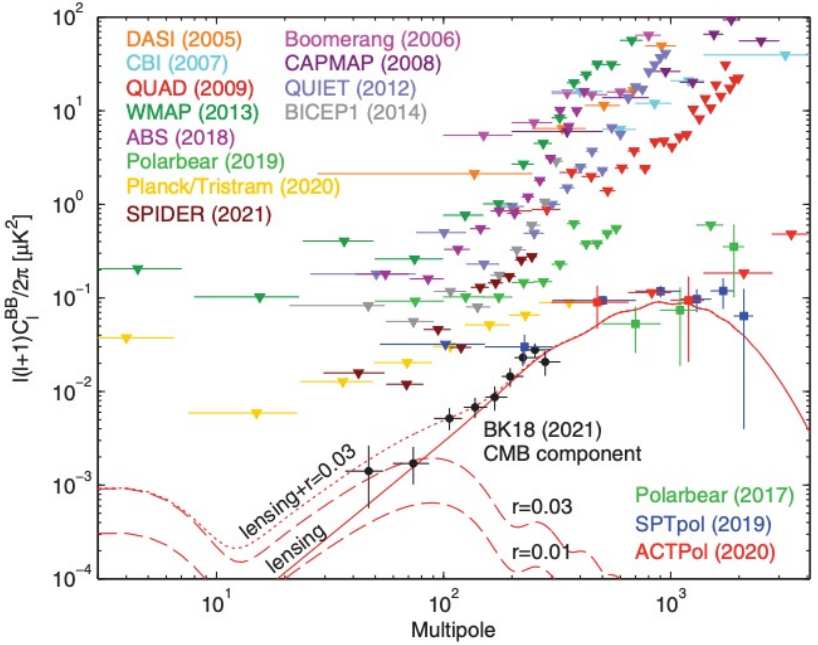


FIG. 21.— NET per detector histogram for the *Keck Array* in 2013

Superconducting IC array performance



Steve K. Choi *et al* JCAP12(2020)045

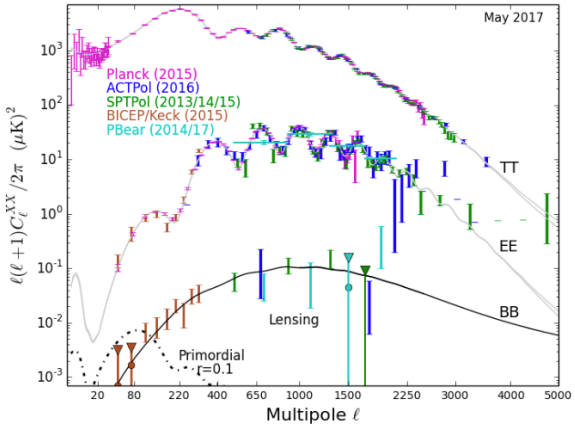


PHYSICAL REVIEW LETTERS **127,** 151301 (2021)

Conclusions slide from 5 yrs ago still correct?

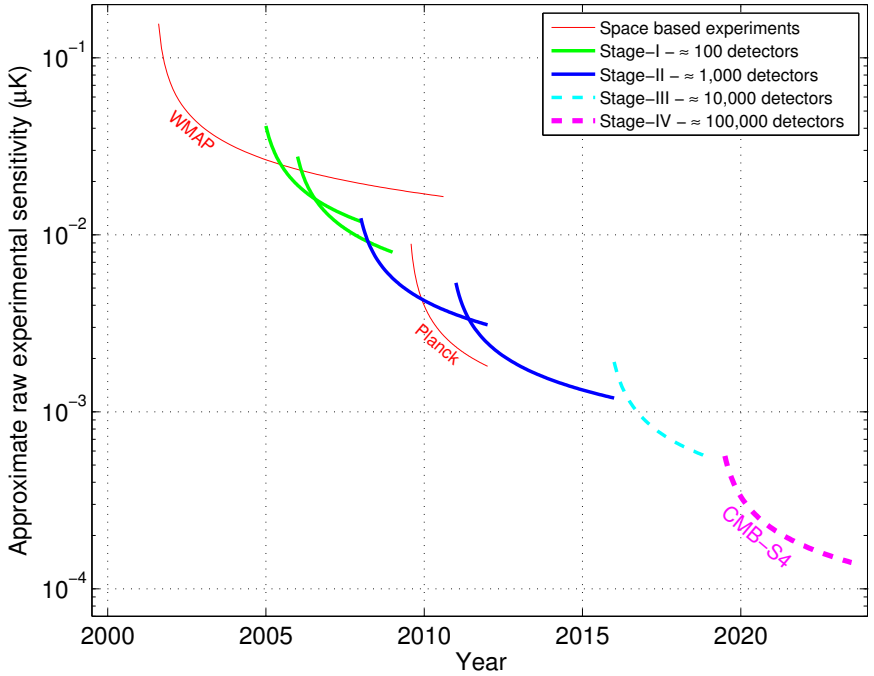
Final Thoughts

1. Wave of excitement and activity in CMB research has not yet crested. CMB is the gift that keeps on giving.
2. Detector community has realized many aspects of the 'ideal detector array'
3. Increased quantity of existing detector technology meets the needs of next-generation experiments (like CMB-S4)
4. CMB imagers will benefit most from innovations in readout and detector packaging. Detectors are in the bag!



Challenge #1: Detector Production

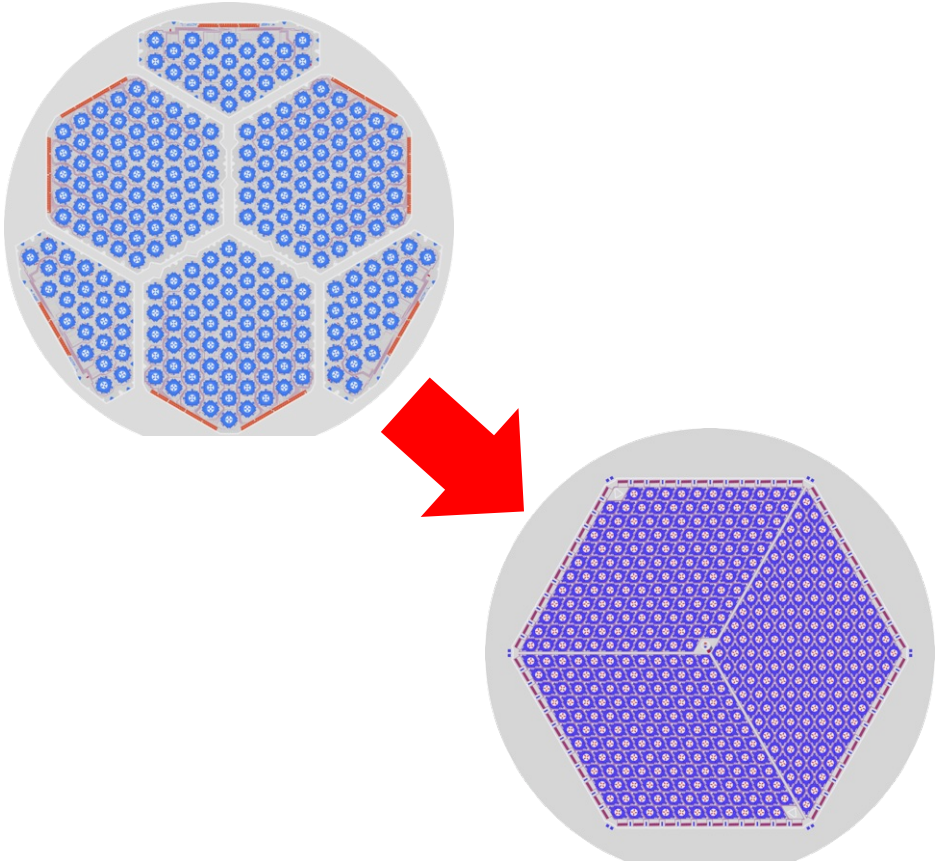
- CMB-S4 requires 0.5M sensors, 500 wafers, 9m² of silicon!
- This is x10 larger than what has been produced and deployed to date.



Increased wafer size: 150mm

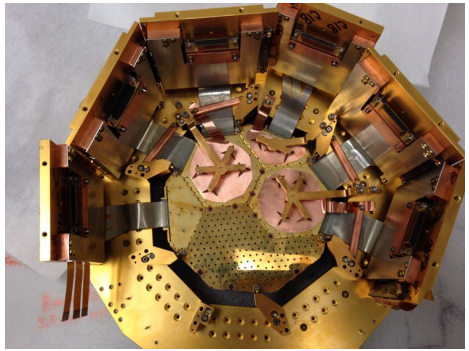
- Increased wafer size a common industry approach to increase throughput / decrease cost

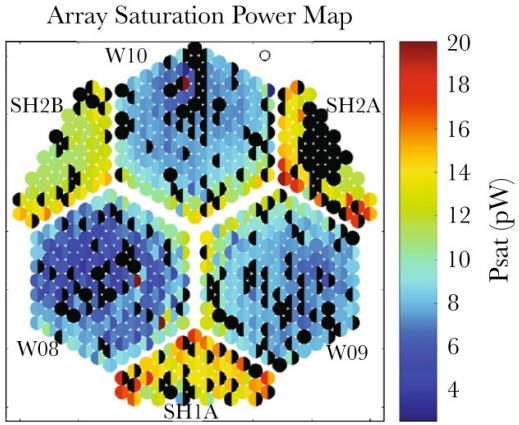
- 150mm substrates now state of the art for CMB sensor array fabrication



Improved uniformity and repeatability

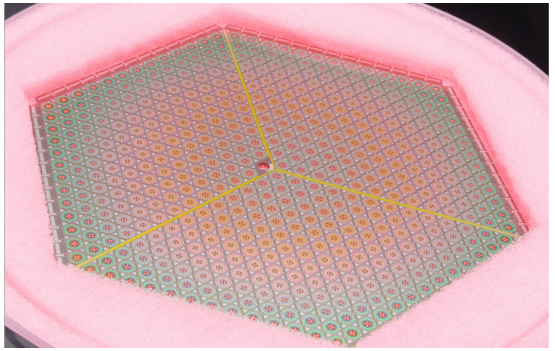
Previous generation arrays

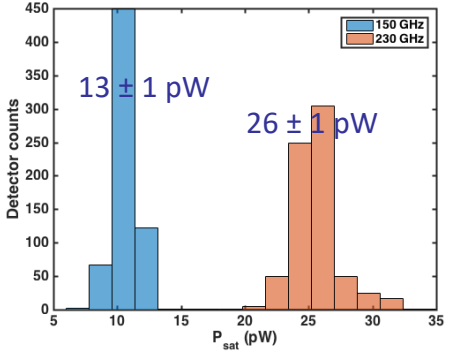




Grace et al JLTP 176 (2014)

Current generation arrays

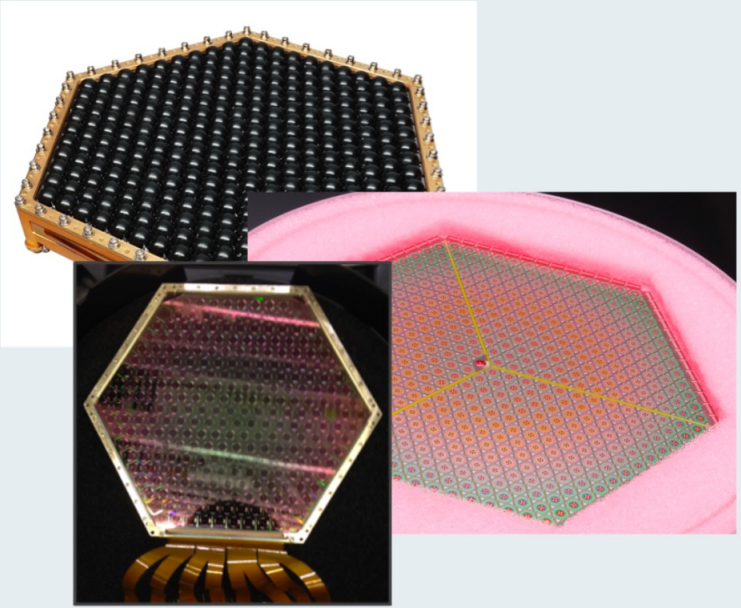




Ho et al. SPIE 991418 (2017)

>150 mm?

150 mm wafers



Go bigger?

source: extremetech.com

- Cost prohibitive
- Quantity to produce too small

Solution for CMB-S4: team-up!

1.03 DETECTORS

*Brenna Flaugher** (FNAL)
John Joseph (LBNL)

1.03.01 Detector Management
John Joseph (LBNL)

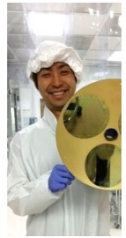
1.03.02 ANL Wafer Fabrication
Clarence Chang (ANL)

1.03.03 SLAC Wafer Fabrication
Dale Li (SLAC)

1.03.04 JPL Wafer Fabrication
Jamie Bock (JPL)
Roger O'Brient (JPL)

1.03.05 NIST Wafer Fabrication
Shannon Duff (NIST)

1.03.06 LBNL/SeeQC Wafer Fabrication
Aritoki Suzuki (LBNL)



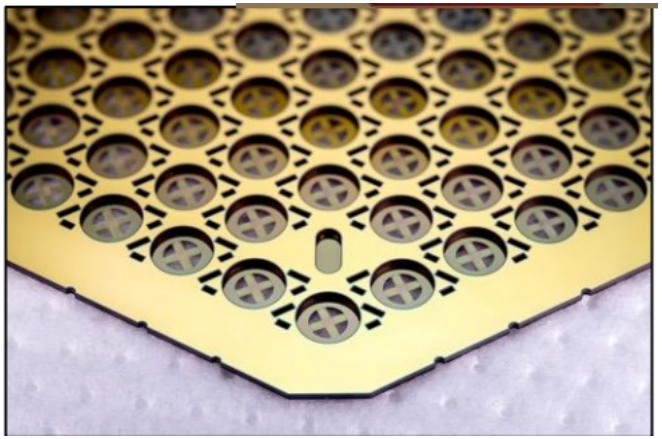
1.03.07 UCB/Marvell Wafer Fabrication
Adrian Lee (UC Berkeley)
Ben Westbrook (UC Berkeley)

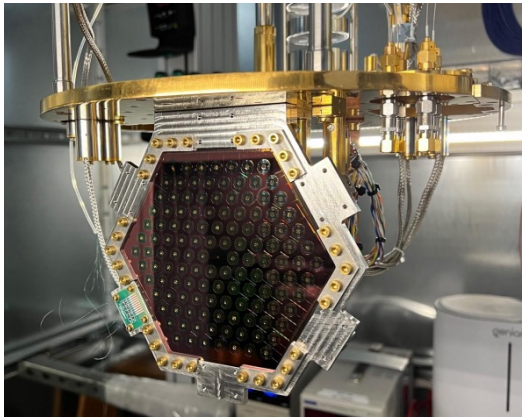
CMB-S4

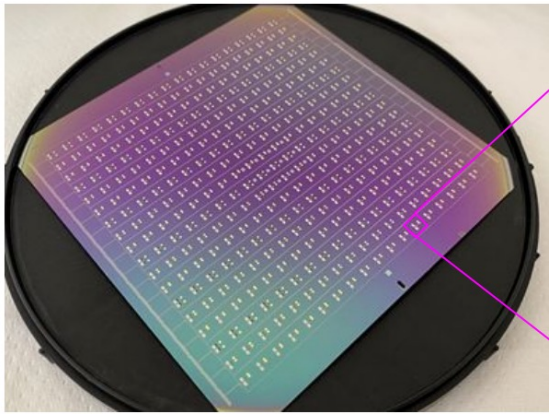
CMB-S4 Collaboration Meeting, May 9-13, 2022

Slide 2

Solution for CMB-S4: team-up!

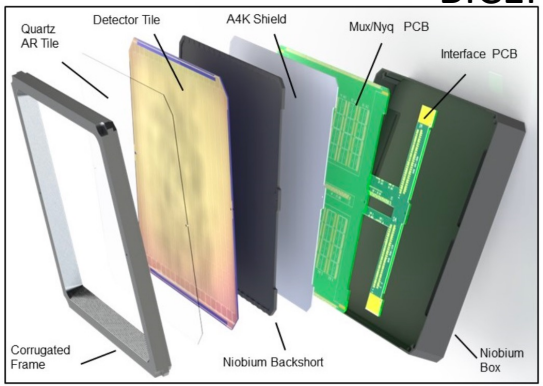


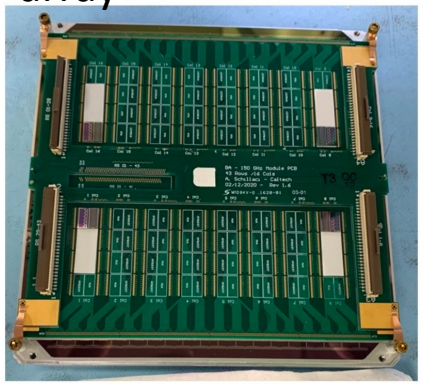




Challenge #2: packaging

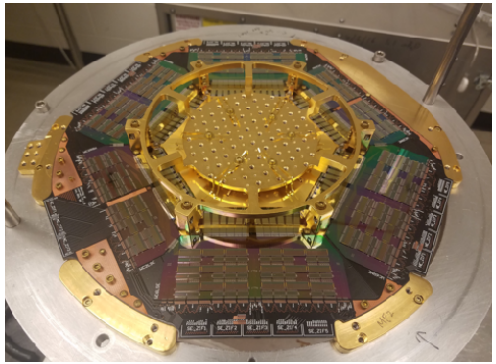
BICEP array



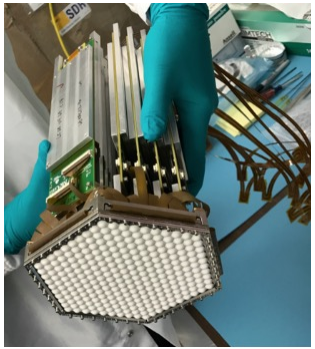


A. Schillaci 2022

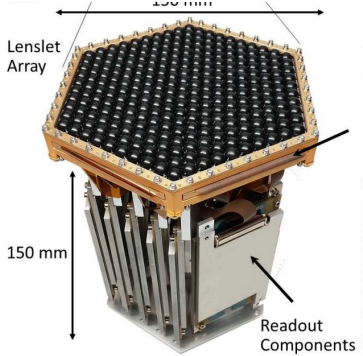
Advanced ACTPol



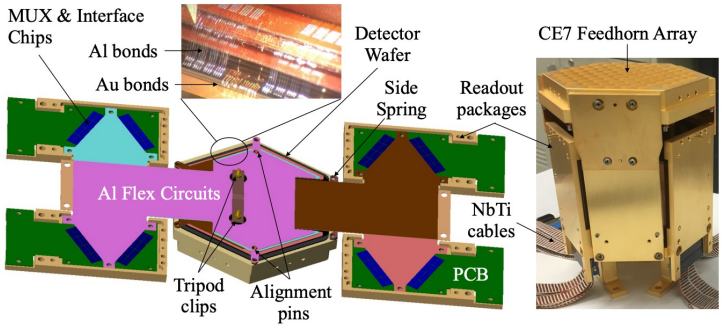
SPT-3G



PB2/Simons Array

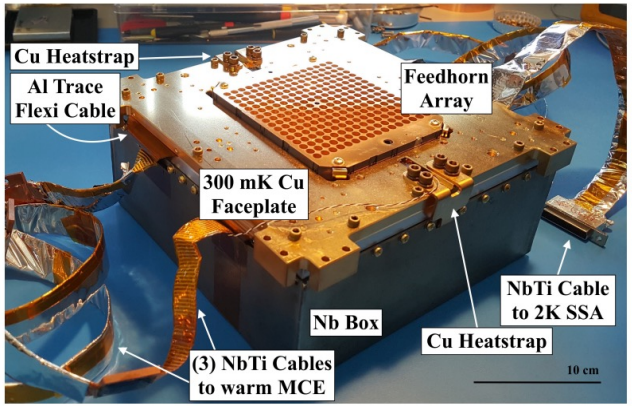


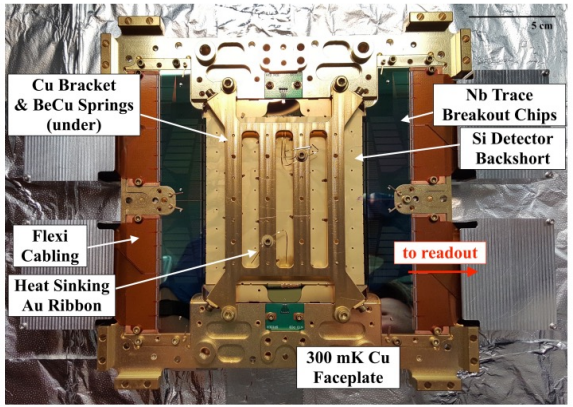
CLASS

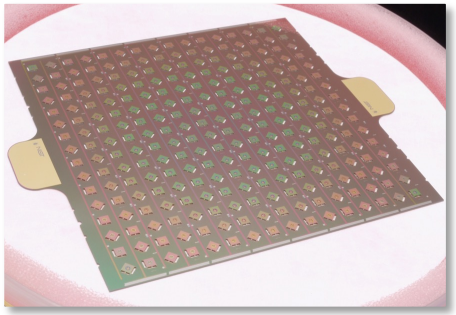


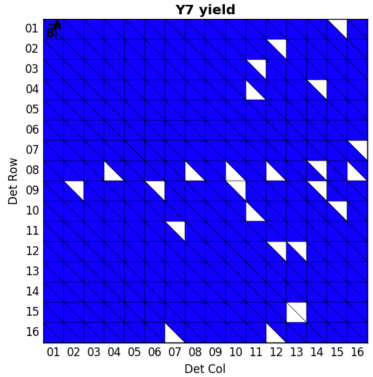
SPIDER 280 GHz example

SPIDER 280 GHz >95% end-to-end yield (defined by acquiring useable IV curves)









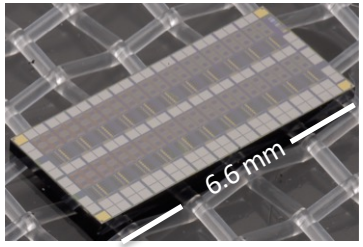
Bergman et al 2018

SQUID multiplexers

Traditional SQUID multiplexing
30,000 deployed pixels

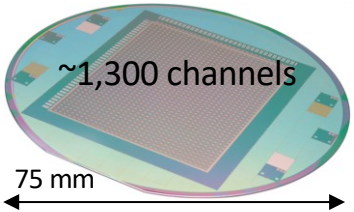
Time division MUX

1D mux



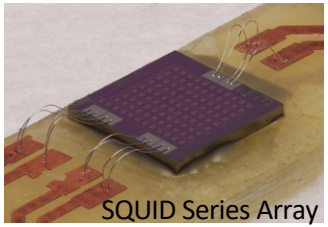
ABS, ACT, ACTPol, AdvACT, BICEP2, BICEP3, CLASS, KECK Array, MUSTANG, SPIDER, ZEUS

2D mux



HAWK+, PIPER, SCUBA2

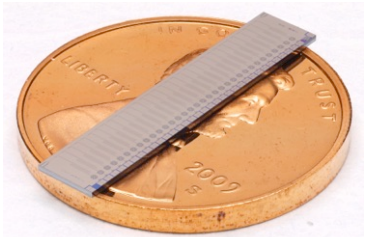
MHz frequency division MUX



APEX-SZ, EBEX, PolarBEAR, PolarBEAR2/Simons Array, SPT, SPTpol, SPT3G

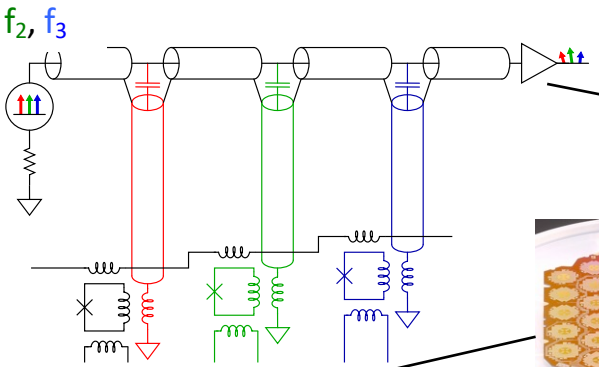
Microwave SQUID multiplexing

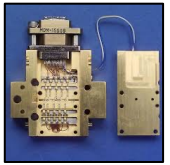
33-channel μMUX chip



a scalable architecture for the readout of large TES arrays

MUSTANG2, Simons Observatory

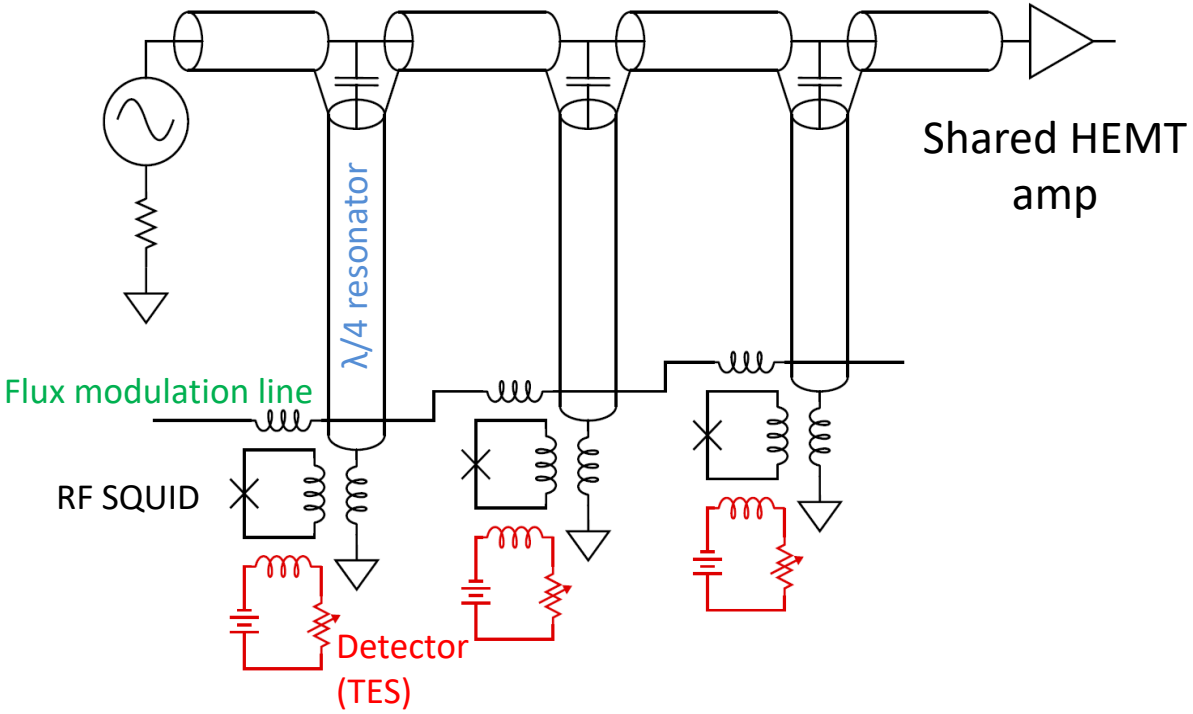


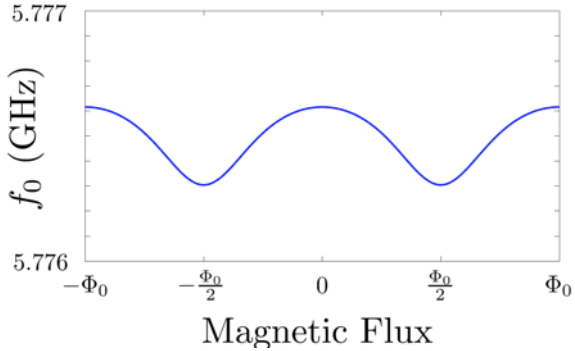


4K LNA

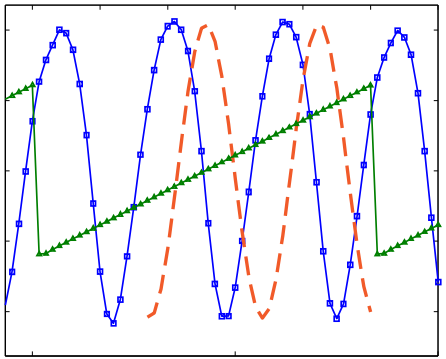
TES array

Microwave SQUID Multiplexing (μmux) Concept



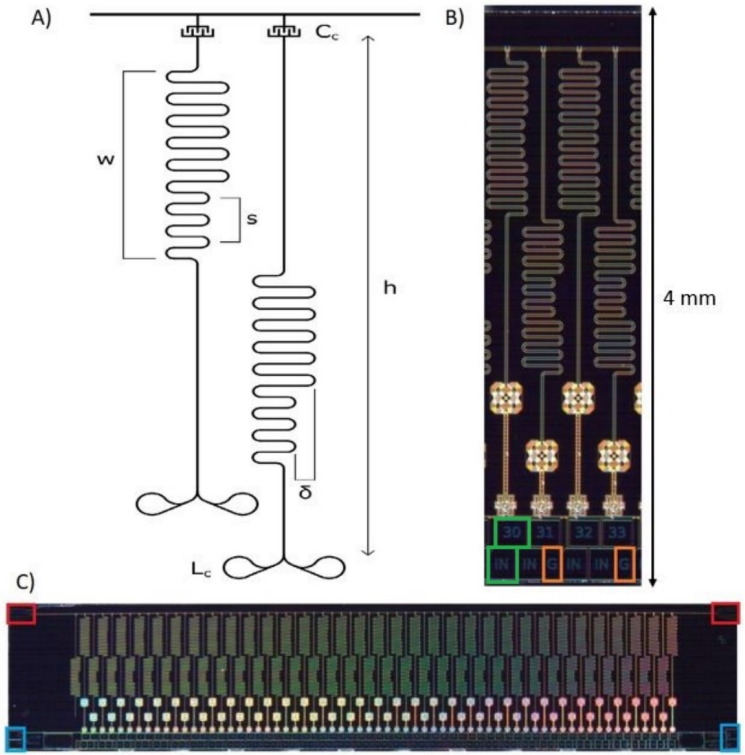


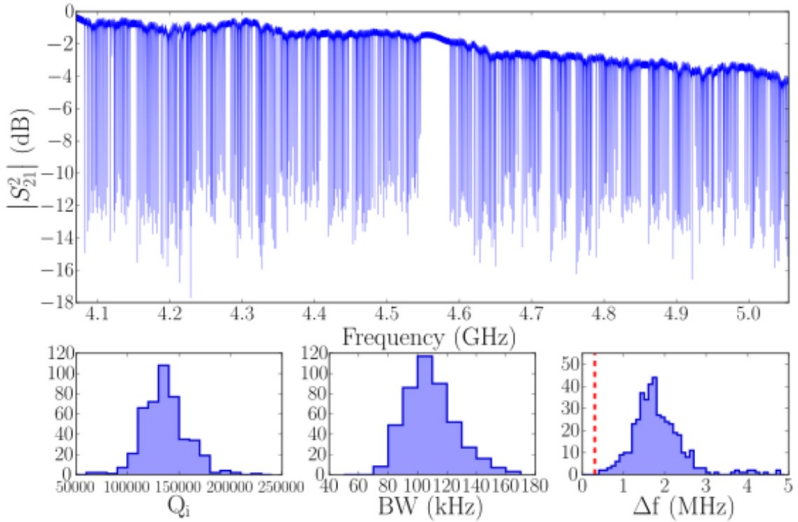
Flux Ramp Modulation



J.A.B. Mates Thesis (2011)

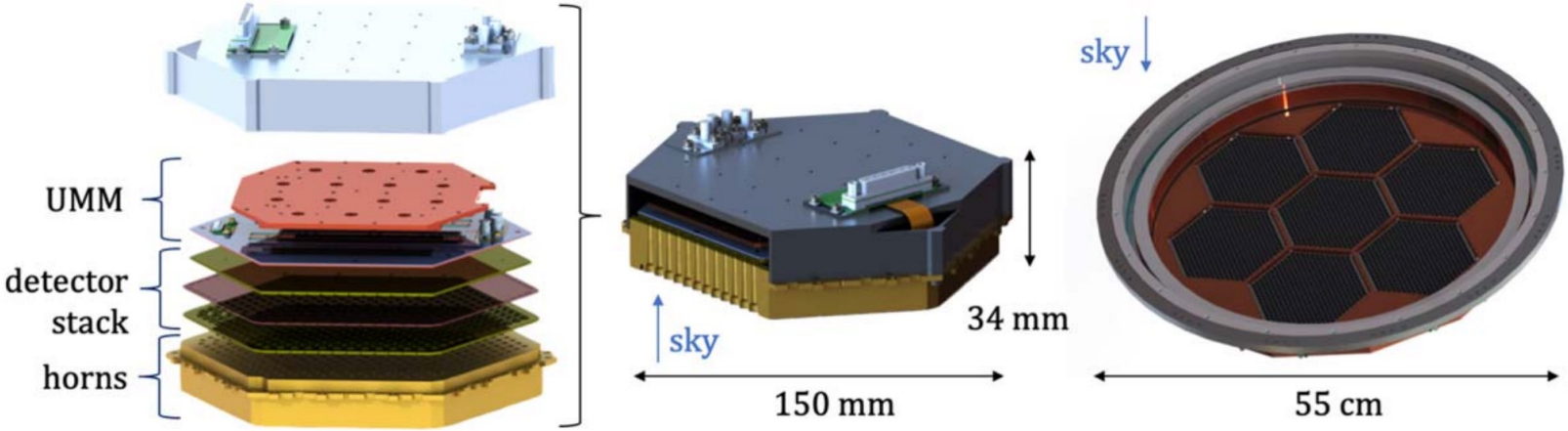
μmux developed for bolometers





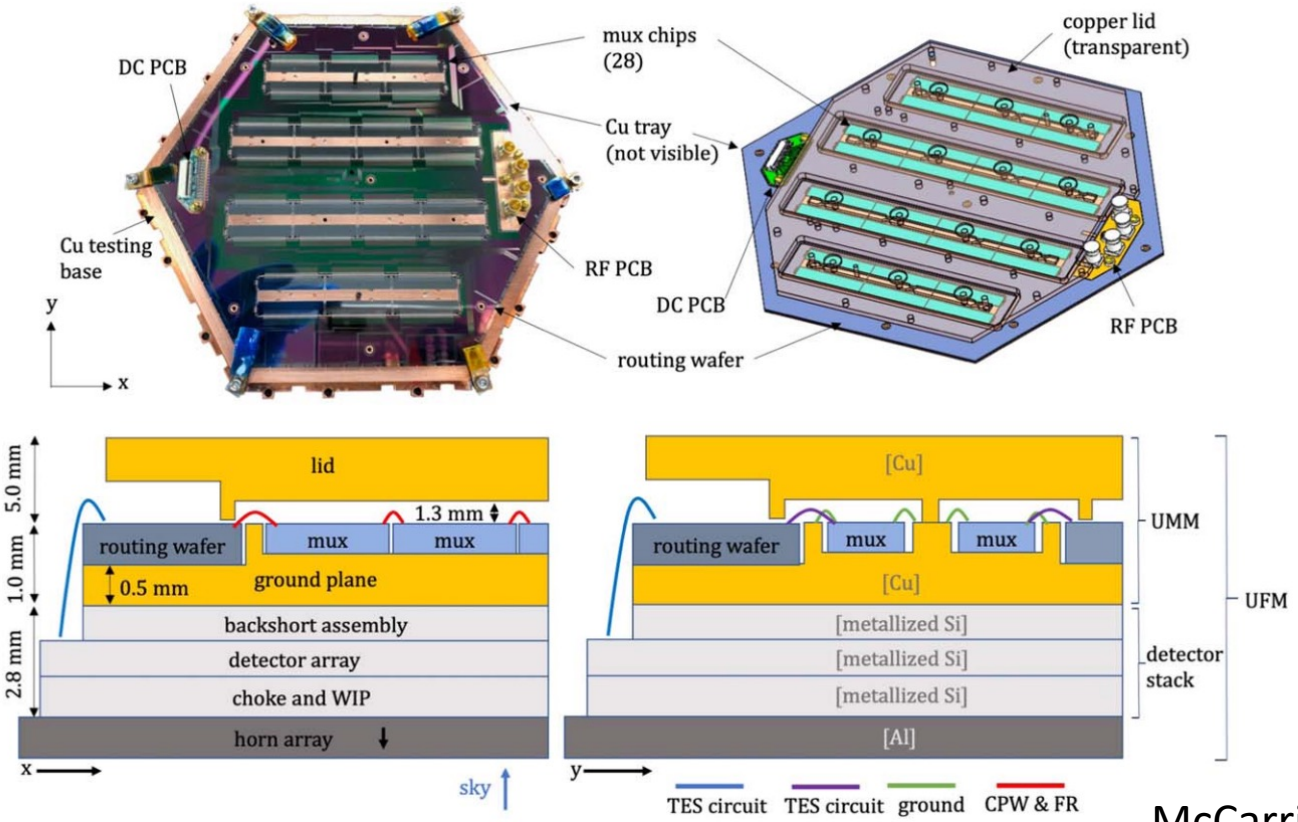
Dober et al 2021
Scalability of 4000 channels in 4-8 GHz

Implementation for Simons Observatory



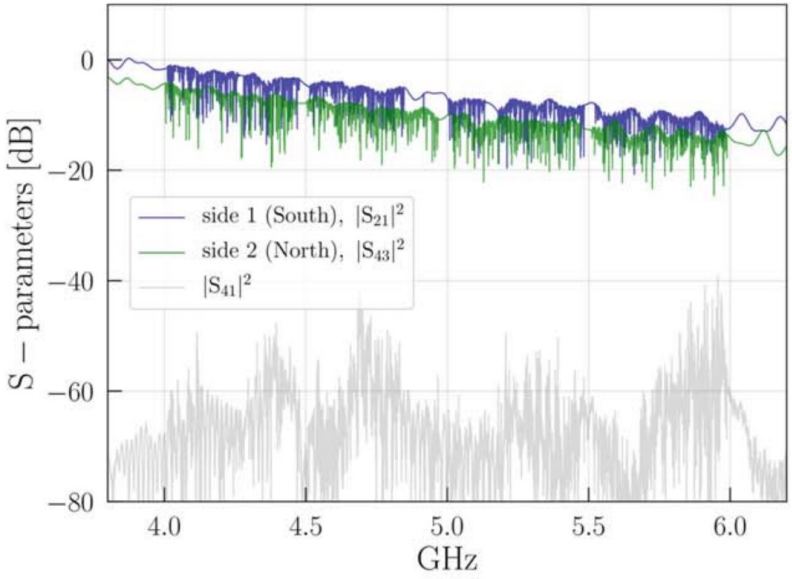
McCarrick et al 2021

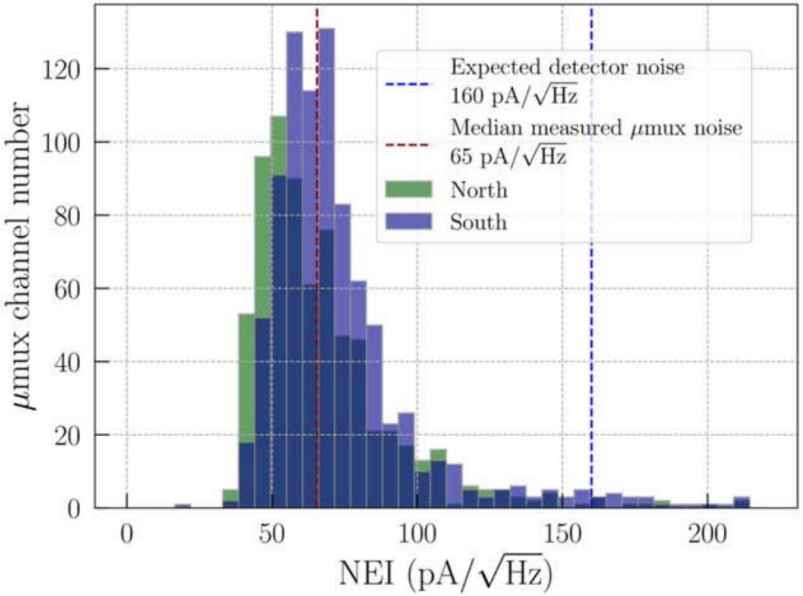
Implementation for Simons Observatory



McCarrick et al 2021

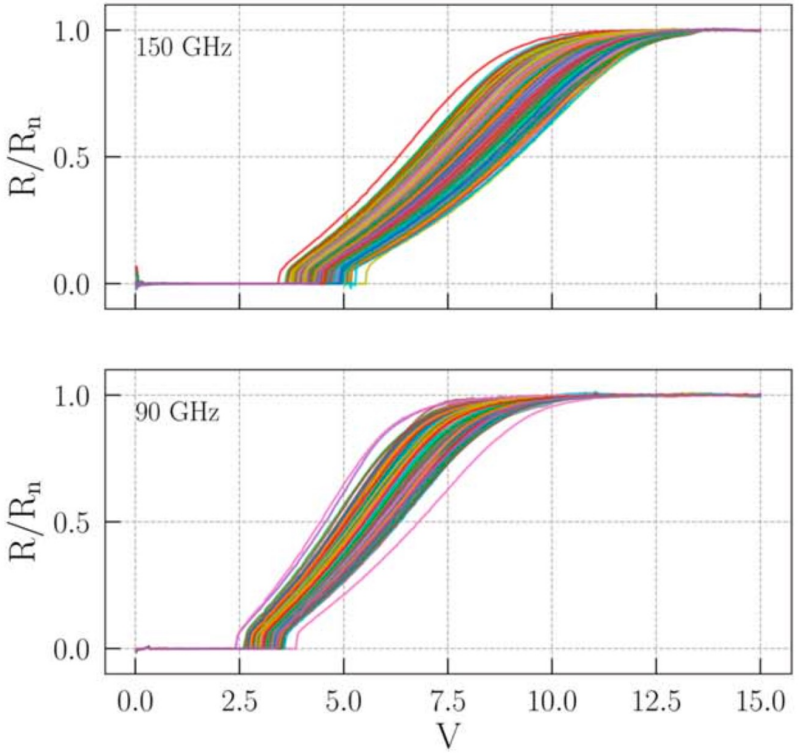
Implementation for Simons Observatory

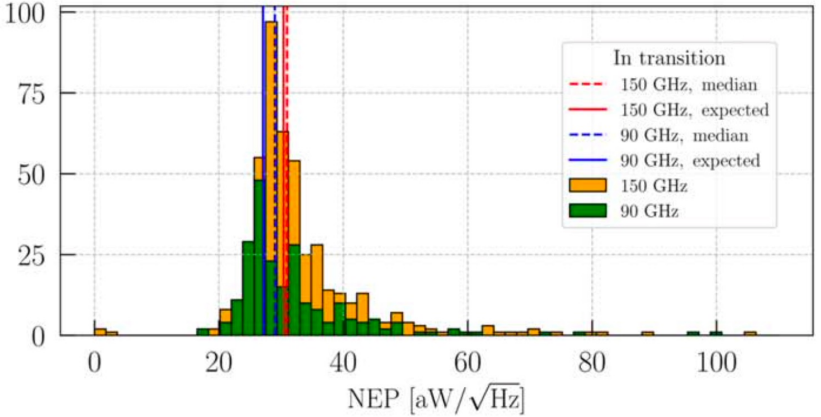




McCarrick et al 2021

Implementation for Simons Observatory





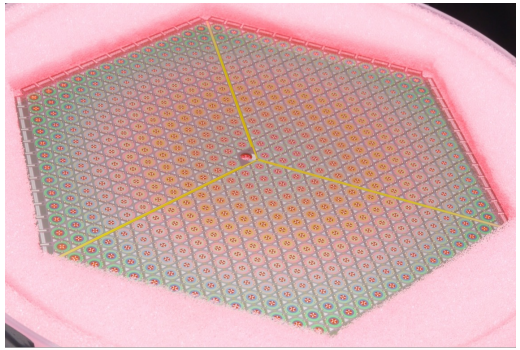
McCarrick et al 2021

on-wafer multiplexing

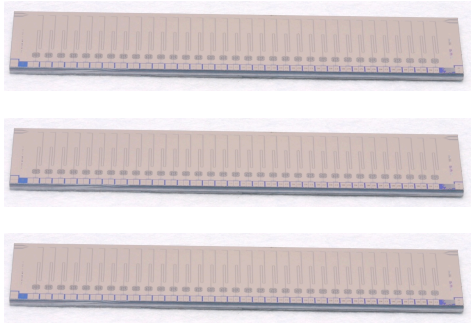
TES array

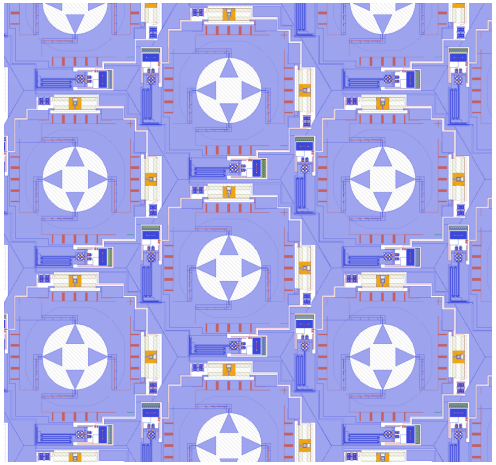
microwave SQUIDs

readout integrated into pixel



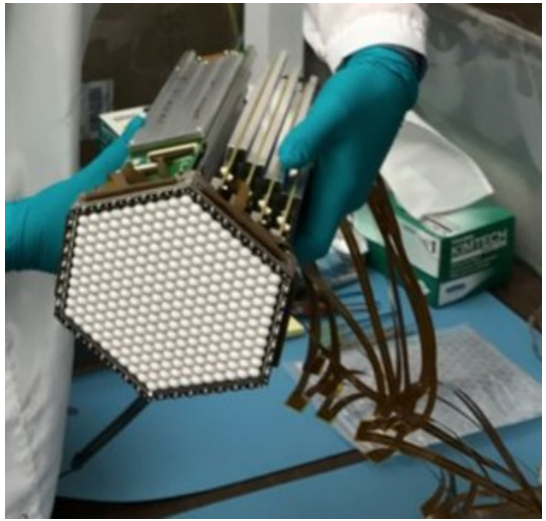
+



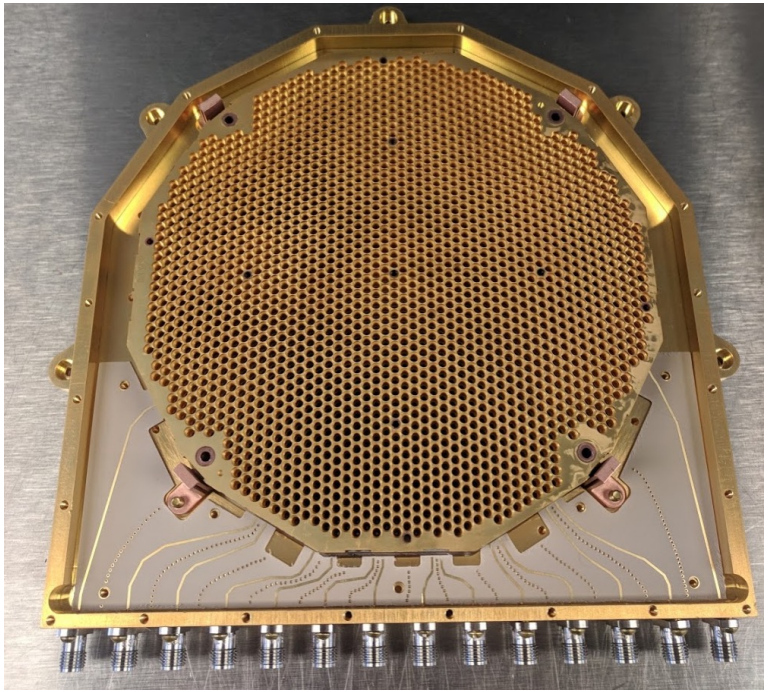


Number of interconnects on/off wafer reduce to 2 coax cables and few DC lines

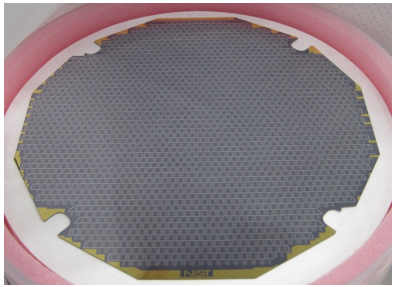
MKID Motivation: Simplified Packaging

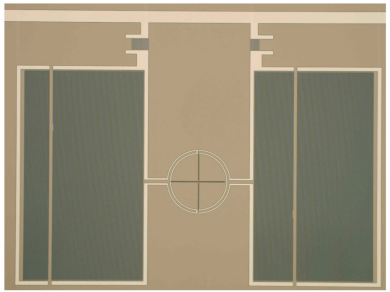


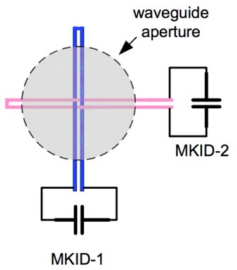
SPT-3G, Benson et al. 2014
90/150/220 GHz, 1626 TES



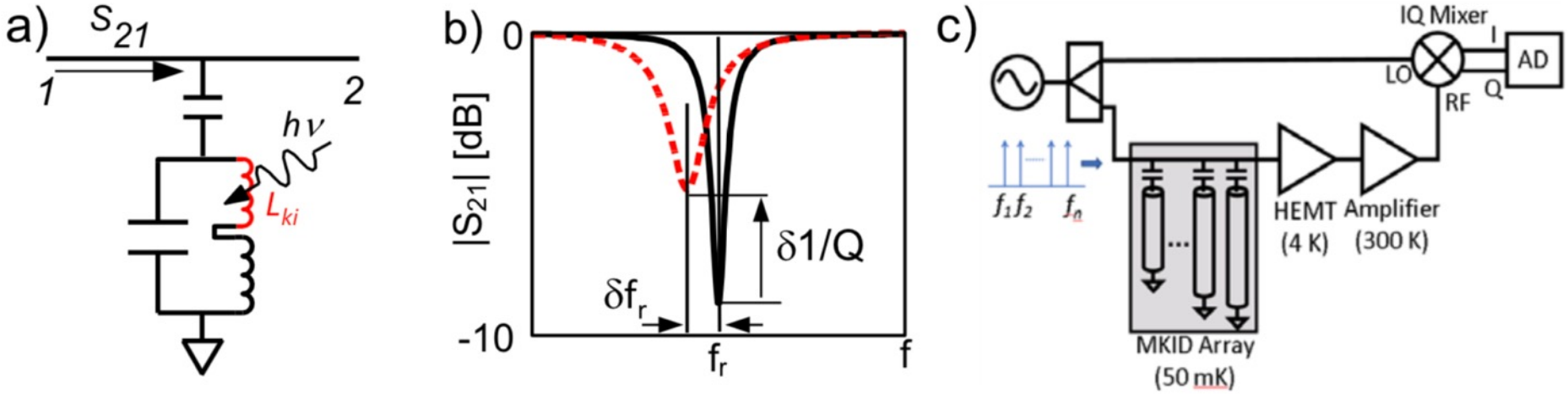
TolTEC, Austermann et al. 2018
280 GHz, 4012 MKIDs







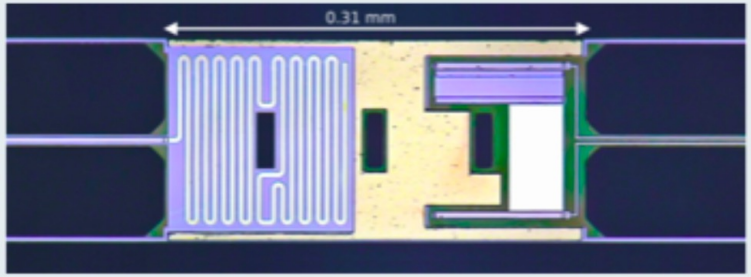
Microwave Kinetic Inductance Detectors (MKIDS)



- First demonstration Day et al. 2003
- Power transduces frequency (or amplitude) shift in RF or microwave resonator

Sensor Comparison

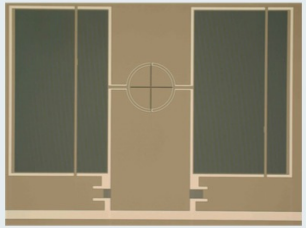
TES Bolometers



Caltech/JPL

- Thermal detector
- Workhorse CMB sensor for last decade (~30,000 currently deployed)
- Fundamental detector noise source: phonon noise
- Mapping speed degrades as $A \times \frac{kT_c}{h\nu}$

MKIDs

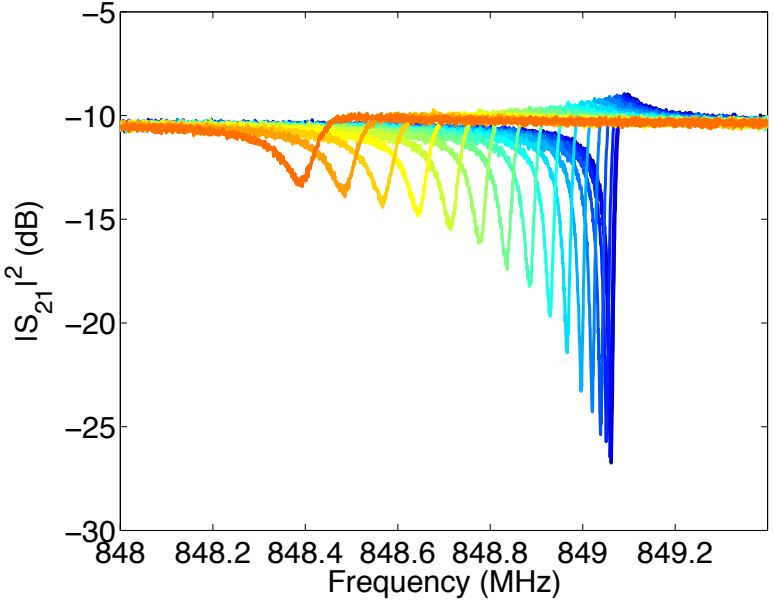


NIST

- Non-equilibrium pair-breaking detector
- Gaining momentum for CMB application
- Fundamental detector noise source: generation-recombination noise
- Mapping speed degrades as $B \times \frac{\Delta}{h\nu}$

MKID motivation: simplified characterization

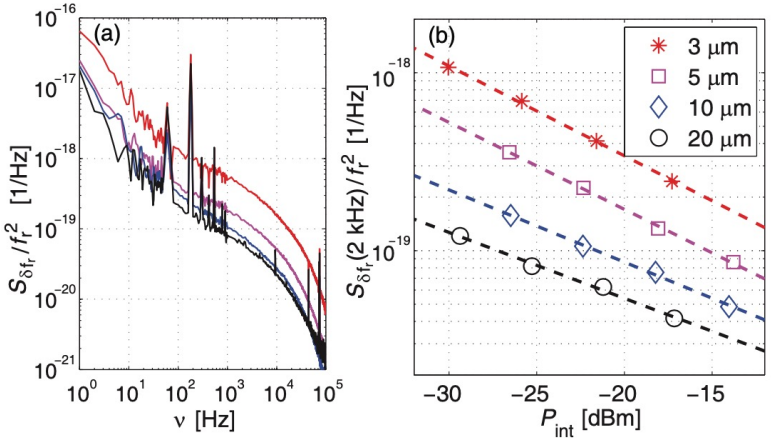
- Microwave transmission sweeps
  - vs temperature
  - vs microwave power
- Full array characterization can be very quick



From my hilarious colleague Jiansong Gao

Why aren't we using MKIDs for CMB?

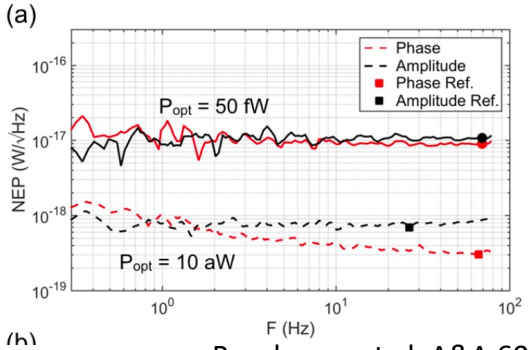
- Low frequency noise
- GR noise
- Multichroic MKID demonstration at CMB frequencies
- On-sky end-to-end demonstration



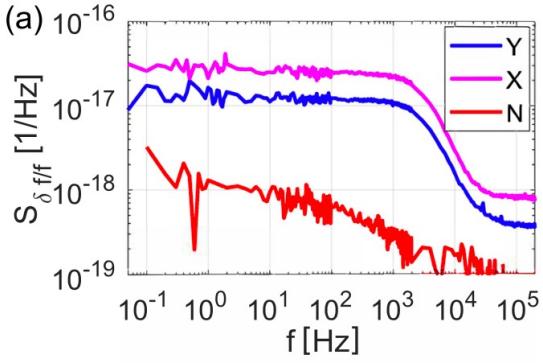
Gao thesis 2008

Why aren't we using MKIDs for CMB?

- Low frequency noise
- GR noise
- Multichroic MKID demonstration at CMB frequencies
- On-sky end-to-end demonstration



Baselmans et al. A&A 601 (2017)

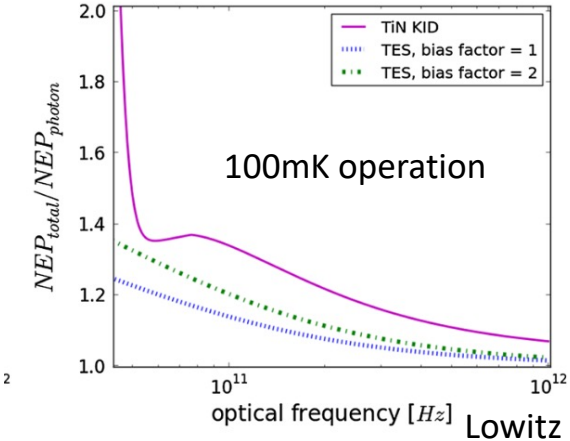


Vissers et al APL 2020

Why aren't we using MKIDs for CMB?

- Low frequency noise
- GR noise
- Multichroic MKID demonstration at CMB frequencies
- On-sky end-to-end demonstration

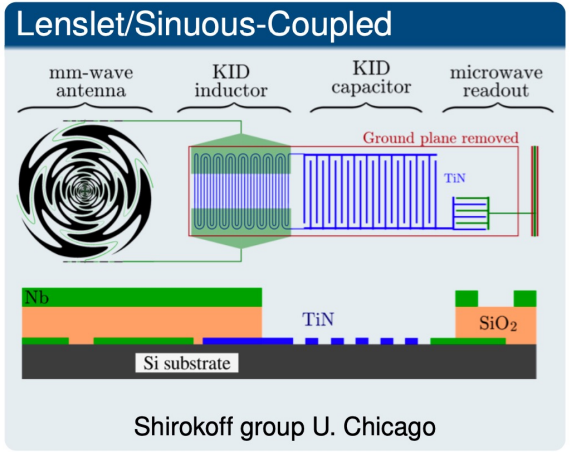
- Generation-recombination noise decreases sensitivity
- Mitigated by making superconducting gap many times lower than the photon energy.
- For lower frequencies places a constraint on Tbath to avoid thermal GR noise.
- Does this practically mean mixed technology focal plane for instruments with frequency coverage < 100 GHz?

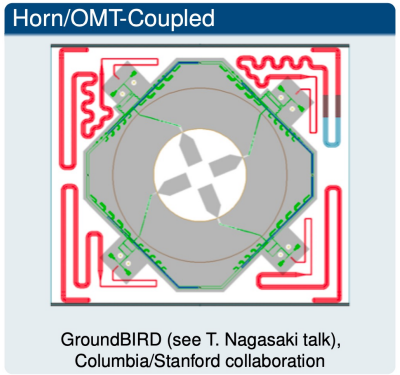


Lowitz et al 2014

Why aren't we using MKIDs for CMB?

- Low frequency noise
- GR noise
- Multichroic MKID demonstration at CMB frequencies
- On-sky end-to-end demonstration

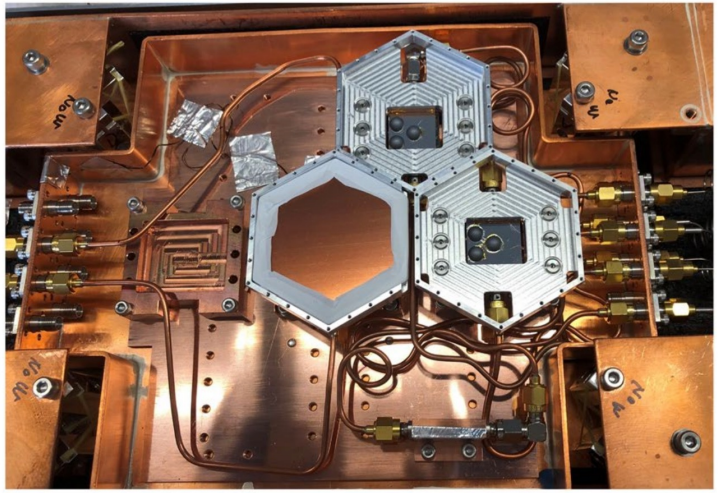




Why aren't we using MKIDs for CMB?

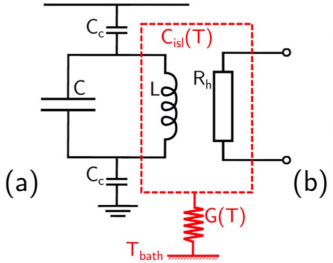
- Low frequency noise
- GR noise
- Multichroic MKID demonstration at CMB frequencies
- On-sky end-to-end demonstration

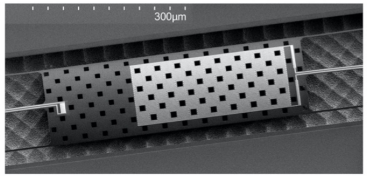
GroundBIRD



Lee et al. 2020

TKIDs for BICEP Array?

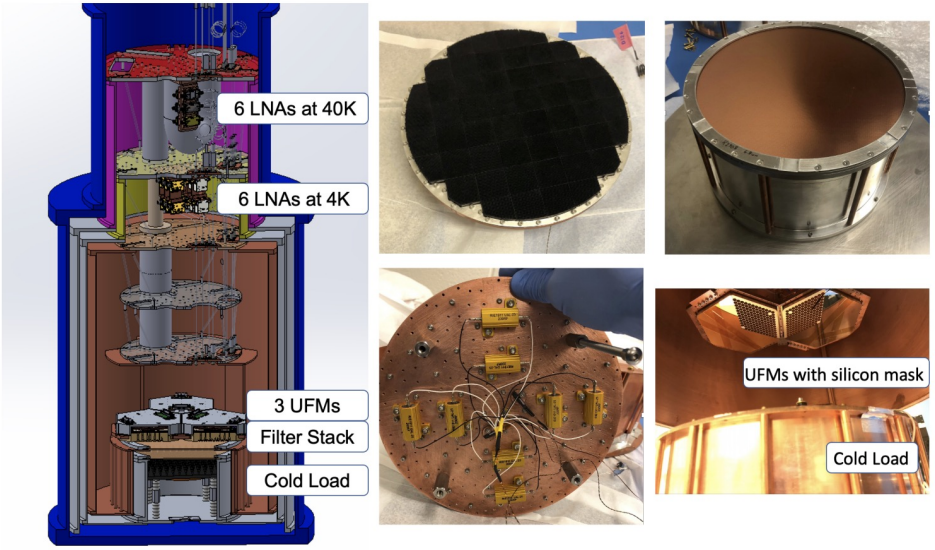




Wandui et al 2020

Challenge #3: Array Characterization

- Characterization of arrays extremely challenging
  - 100mK cryogenics
  - Large mm-wave windows
  - different configurations desirable requiring multiple cooldowns
- Historically this can take months for one array
- Requires well-understood, well-calibrated cryogenic test platforms

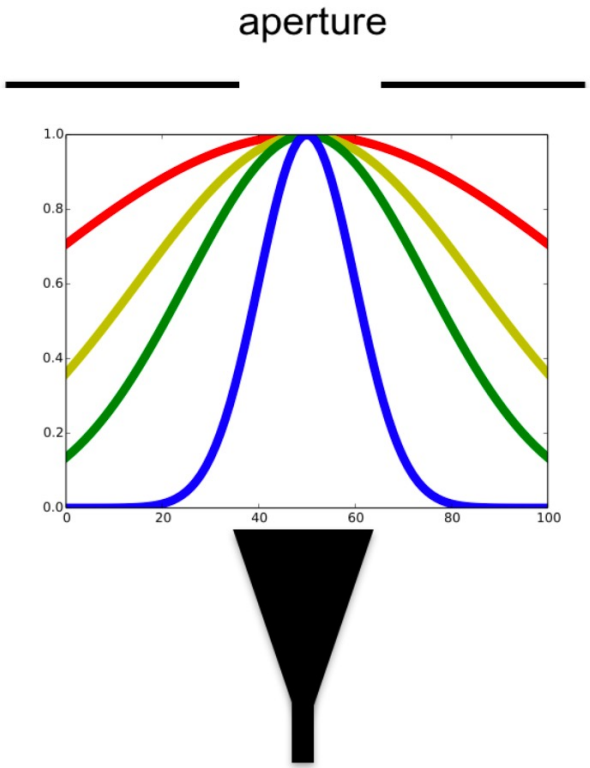


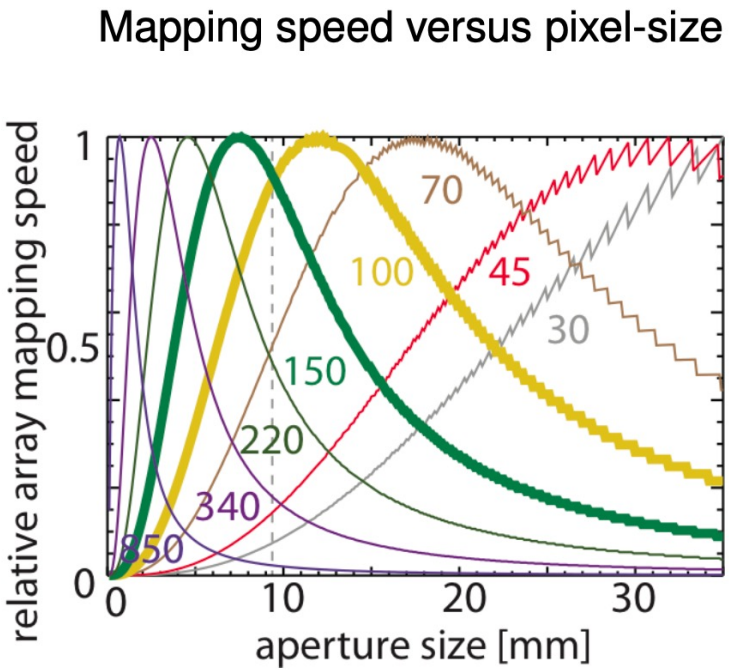
Wang et al submitted to JLTP

New ideas for space implementation

- Heirarchical phased arrays
- on-chip refrigerators

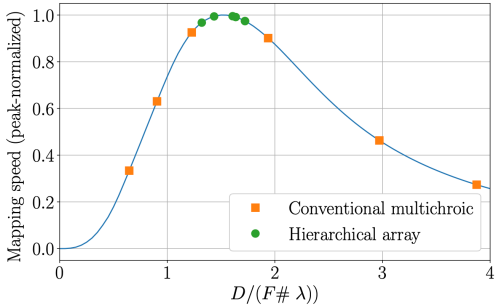
Single diffracting aperture leads to inefficiently

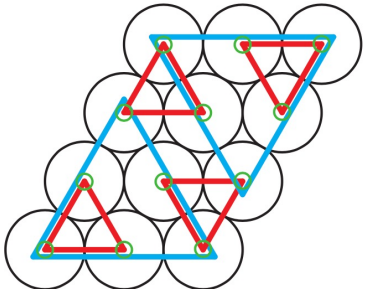


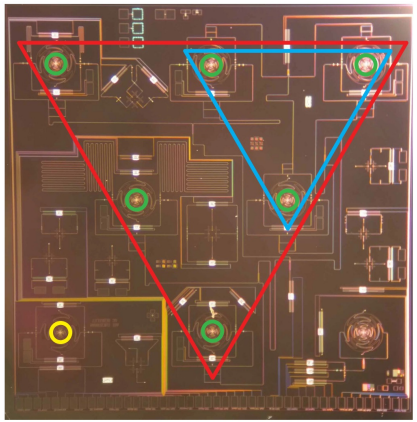


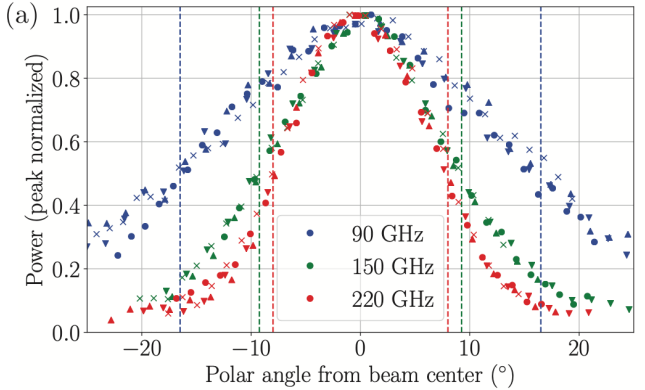
Datta et al. (2014)

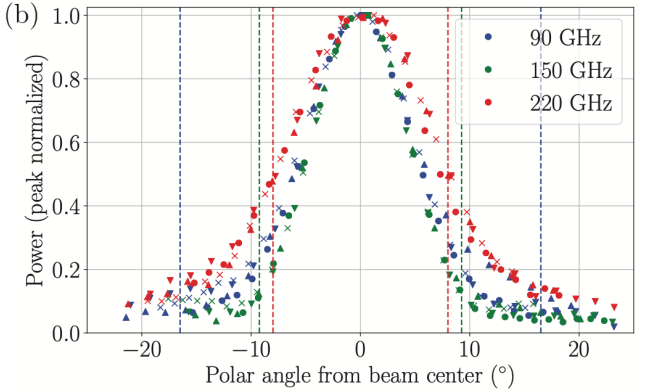
Heirarchical phased arrays





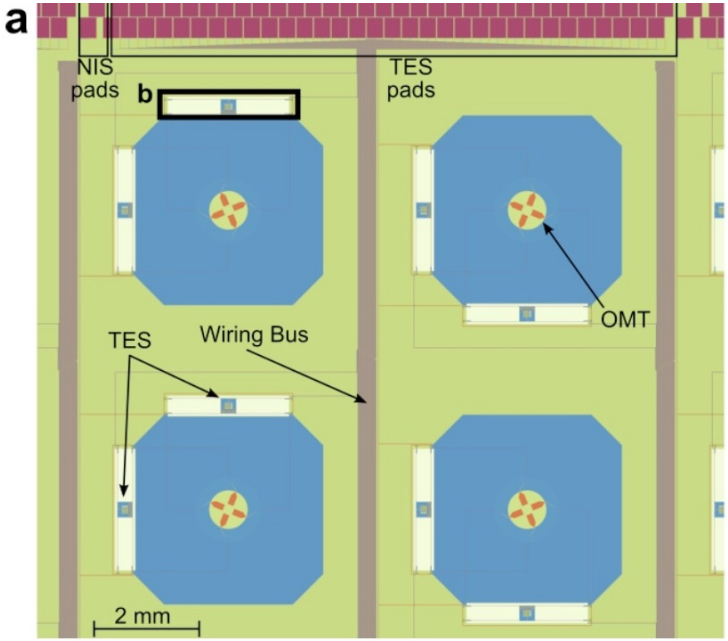


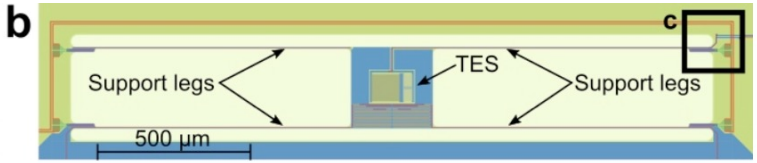


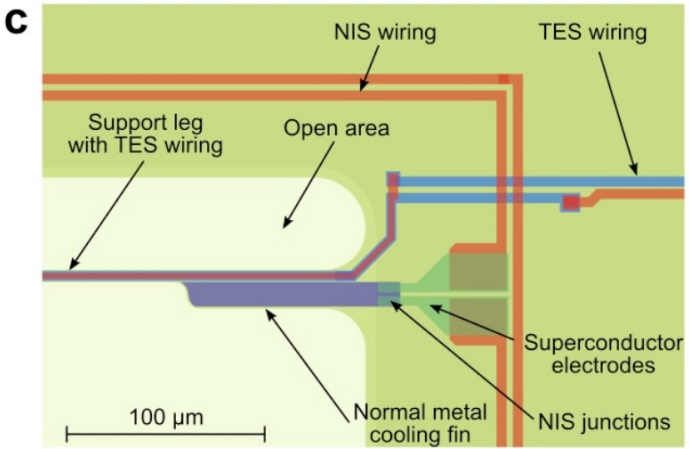


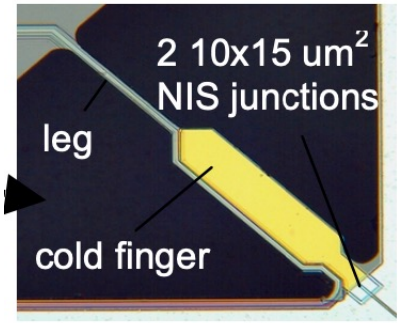
Cukiermann et al 2018

on-bolometer coolers





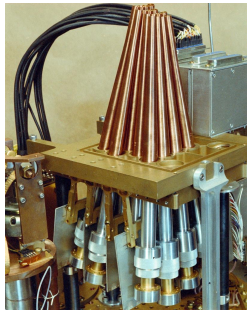


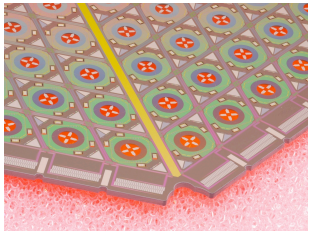


100mK TES performance with 300mK refrigeration techniques

Final thoughts

- Last two decades saw tremendous innovation in superconducting sensors for CMB detection
- For the next decade, need more of today's state-of-the-art but faster, easier to install, reliable. This is a phase change for the field. It will be realized with healthy collaboration
- What we have developed for the ground will be deployed in space.
- The shape of CMB focal planes to come? Plenty of innovative ideas out there. Given landscape, where to put focus?





??

Many Thanks!

- Special thanks to the organizers
- hubmayr@nist.gov
- https://www.nist.gov/programs-projects/long-wavelength-detectors-and-applications